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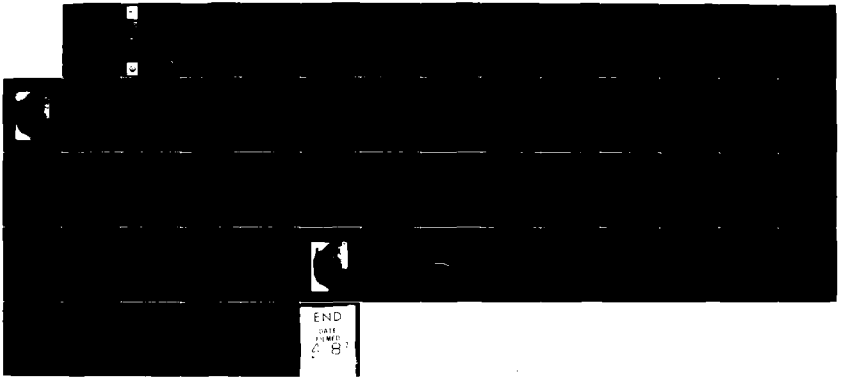

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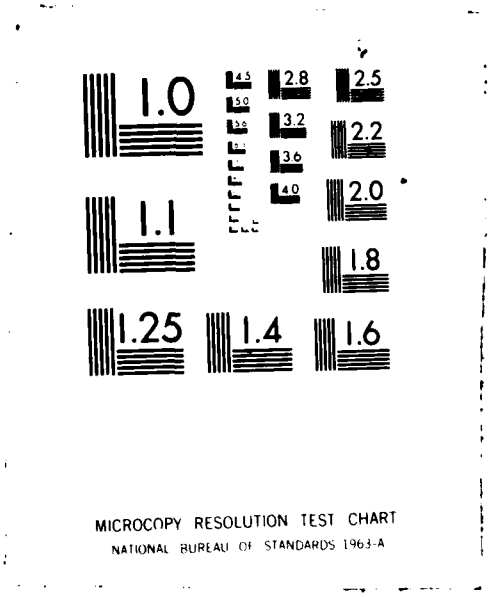
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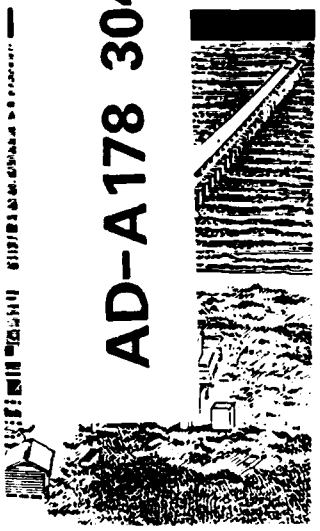

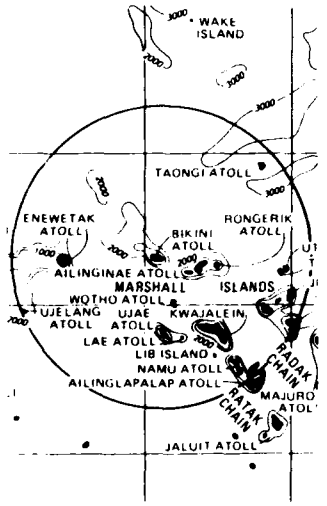

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MISCELLANEOUS PAPER CERC-87-5

PRELIMINARY DESIGN OF A LANDFILL AND REVETMENT ON BIKINI ISLAND, REPUBLIC OF THE MARSHALL ISLANDS

by

Orson P. Smith, Yen-hsi Chu

Coastal Engineering Research Center

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Topsoil on Bikini Island, which is located 2,500 miles southwest of Hawaii at 11°35' N, 165°25' E, was contaminated by radioactive fallout from nuclear weapons tests in the late 1940's and early 1950's. The uptake of this radioactive fallout, primarily cesium-137 in plants, has prevented resettlement of the island by the native population. One alternative solution proposed by the congressionally appointed Bikini Atoll Rehabilitation Committee involves removal of the contaminated topsoil and placement of the excavated material as a landfill on the 2,500-ft-wide reef flat adjacent to the eastern (windward) shore of the island. This paper explores that alternative by first developing an extremal wave climatology offshore of Bikini Island from 21 years (1959-1979) of typhoon data published by the Joint Typhoon Warning Center on Guam.

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19. Abstract (Continued).

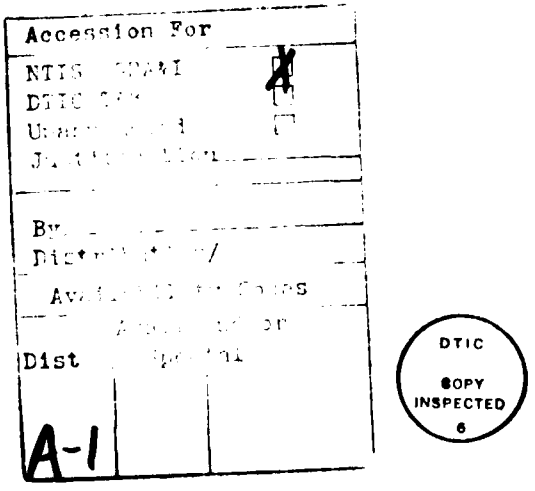
Deepwater wave conditions just offshore of the reef are estimated and transformed to the point of breaking at the edge of the reef. Storm surge is estimated based on these same parameters. Wave setup on the reef flat is estimated based on the simulated breaking conditions. Given an estimate of the elevated water level across the reef caused by storm surge and wave setup, depth limitations and fractional decay are estimated to define wave conditions at the toe of the proposed revetment. A rubble-mound revetment design stable in these conditions, armored by coral limestone quarried from the reef flat, is then formulated and corresponding material quantities estimated.

PREFACE

The technical analyses summarized in this report were authorized by the US Army Engineer Division, Pacific Ocean, in the form of an Intra-Army Order for Reimbursable Services, Number E6860007, dated 31 January 1986. The authors, Mr. Orson P. Smith (Principal Investigator) and Dr. Yen-hsi Chu, both of the Coastal Design Branch of the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES), were the primary contributors to the work, but a number of others were instrumental in seeing the work through to completion. Ms. Lynda J. Brooks prepared the bibliography and performed the word processing. The technical materials and information provided from Dr. Arthur S. Kubo of the BDM Corporation, McLean, Va., and member of the Bikini Atoll Rehabilitation Committee; Dr. Katherine Agegian of the Department of Oceanography, University of Hawaii; and Dr. James E. Maragos of the Environmental Resources Section, US Army Engineer Division, Pacific Ocean, are gratefully acknowledged. The assistance in the course of the analyses by Ms. Debra L. Rouse and Mr. Roland E. Pool, both contract students at CERC, is also appreciated. This report was edited by Ms. Jamie W. Leach of the Information Products Division, WES.

The efforts at the CERC were directed by Dr. James E. Houston, Chief of CERC, Mr. Eugene Chatham, Chief of the Wave Dynamics Division, and Dr. Fredrick E. Camfield, Chief of the Coastal Design Branch.

Director of WES during the course of the work was COL Allen F. Grum, USA. Commander and Director during publication was COL Dwayne G. Lee, CE. Technical Director was Dr. Robert W. Whalin.



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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
fathoms	1.8288	metres
feet	0.3048	metres
inches	2.54	centimetres
knots (international)	0.5144444	metres per second
miles (nautical)	1.8520	kilometres
miles (US statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square miles	2.589998	square kilometres
square yards	0.8361274	square metres
tons (US short)	0.909	metric tons
yards	0.9144	metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F - 32). To obtain Kelvin (K) readings, use K = (5/9) (F - 32) + 273.15.

PRELIMINARY DESIGN OF A LANDFILL AND REVETMENT ON BIKINI ISLAND, REPUBLIC OF THE MARSHALL ISLANDS

PART I: INTRODUCTION

Background

1. Nuclear weapons tests conducted by the US Government in 1946 forced the removal of the people of Bikini Atoll from their homeland. These tests ended in 1958 after 23 detonations had resulted in contamination of the atoll's 23 islands with radioactive materials. The two main islands of the atoll, Bikini (0.9 square mile)* and Eneu (0.4 square mile), were declared safe for resettlement in 1968, but tests in 1978 revealed that coconut palms and other plants on the island contained dangerous concentrations of the radionuclide, cesium-137. The atoll was again evacuated in August 1978.

2. Congress formed the Bikini Atoll Rehabilitation Committee (BARC) with the general objective of assessing technical and economic feasibility of rehabilitating the Bikina Atoll for resettlement by the people of Bikini. BARC-sponsord studies indicate that most of the contamination exists in the top 12 in. of soil on Bikini Island. Because the plant roots grow in this top 12 in., they concentrate the radioactive contaminants. The principal alternatives for mitigating this situation proposed to date include:

a. Stripping and removing the contaminated topsoil and dumping the excavated material at selected sites in the atoll lagoon.

b. Stripping and removing the contaminated topsoil and using the excavated material to create a causeway between Bikini Island and adjacent Eneu Island.

c. Stripping and removing the contaminated topsoil and utilizing the excavated material to create a landfill on the 2,500-ft-wide reef flat adjacent to the eastern (windward) side of Bikini Island.

d. Hydraulically flushing the topsoil in situ with seawater to deactivate the uptake of contaminants by plants.

e. Treating the topsoil with specially formulated chemicals to retard the uptake of contaminants by plants.

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

Scope

3. Preliminary design of alternative c is the subject of this report. The analyses summarized in the remainder of the report are intended only to assess the constructibility of a contained landfill on the Bikini Island eastern reef flat, with appropriate protection of the landfill from the extreme effects of waves and currents. Some options are also discussed for added features or special construction methods which might prevent or mitigate certain potential environmental impacts hypothesized in previous BARC work. These potential impacts include loss of the sandy beach on the inshore side of the reef flat and harm to reef organisms by heavy concentrations of suspended sediments which might accompany construction activities. Preliminary estimates of material quantities are made for application by others in estimating the construction cost of this alternative. Suggestions are made throughout the report as to what additional field data collection efforts and engineering analyses would be appropriate for a final detailed design.

Physical Setting

4. Bikini Atoll is located approximately 2,500 nautical miles (n.m.) southwest of Hawaii at 11°35' N latitude and 165°25' E longitude in the northern Marshall Islands. Nearby lands of note include Wake Island, 470 n.m. to the north; Kwajalein Atoll, 190 n.m. south-southwest; Enewetak Atoll, 190 n.m. west; and Guam, 1,250 n.m. west. The general vicinity of Bikini Atoll is illustrated in Figure 1. The northern Marshall Islands consist entirely of coral reef atolls atop volcanic seamounts. The slopes of these seamounts plunge rapidly to oceanic depths. A number of submerged seamounts or "guyots" are also present in the region.

5. Bikini Atoll is a ring of 23 islands and adjacent shallow coral reef surrounding a lagoon of approximately 240 square miles in surface area, as illustrated in Figure 2. The lagoon has an average depth of 145 ft. The total exposed land area of the atoll is about 3.4 square miles, including 0.6 square mile of intertidal reef flat and sandy beach. Bikini Island is the largest island with a land area of 0.9 square mile. Eneu Island, 2.5 n.m. south of Bikini Island, is the second largest island with a land area of 0.4 square mile. These are the only two islands of the atoll physically

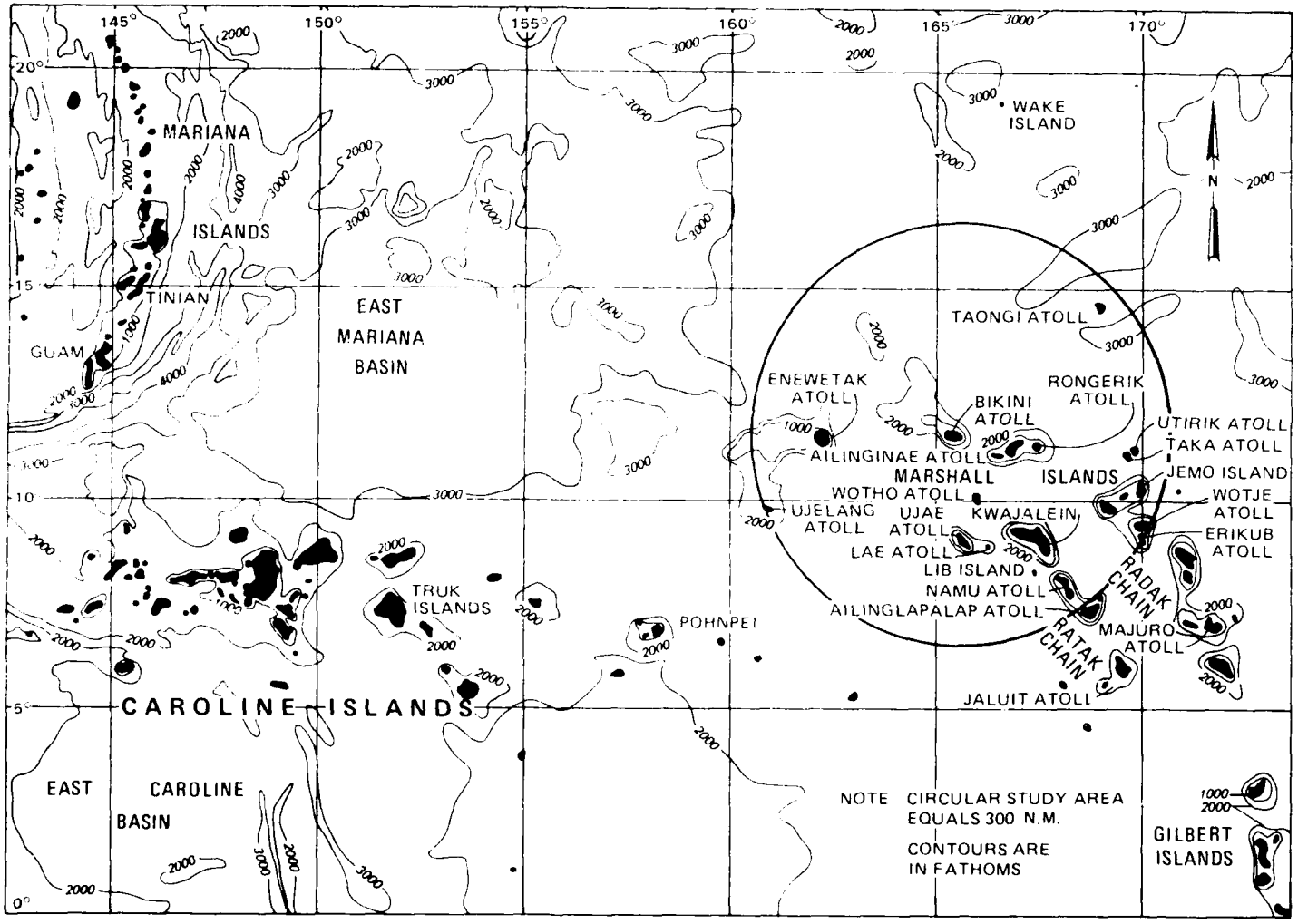

Figure 1. Marshall Islands and vicinity

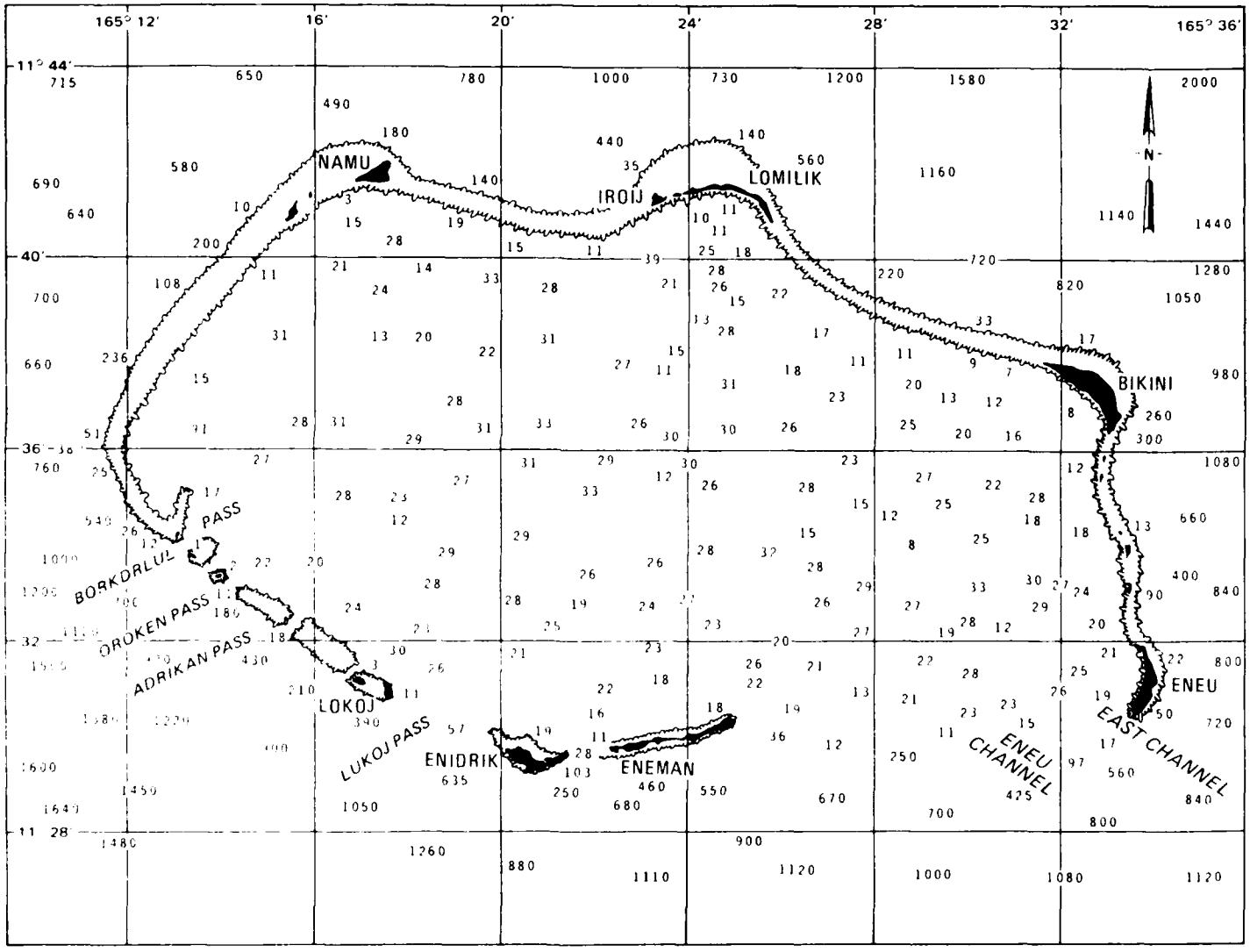

Figure 2. Bikini Atoll (depths in fathoms, grid lines 4 n.m. apart)

suited for permanent settlement with topographic elevations [illegible] 11 ft above mean high water (mhw). The other islands are [illegible] low to be safe from high waves and water levels accompanying [illegible] storms.

6. Bikini Island itself is a cresent-shaped land mass, [illegible] ure 3, forming the northeast corner of the ato... The [illegible] consists almost entirely of coral sand beaches with slopes [illegible] tending generally from 8 or 9 ft above mhw to about [illegible] outcrops also exist on the southeast point where the [illegible] most narrow. The 1978 aerial photograph (Figure 3) indicates that [illegible] island is covered with palm trees and other vegetation, with some [illegible] and other structures (now abandoned) along the lagoon shore. The reef flat, though very irregular on a small scale, extends in places up to [illegible] offshore of the island, at about 3 ft below mhw or the approximate [illegible] of average low tide. It is possible at the time of average low tide [illegible] on exposed coral to the edge of the reef flat. Beyond the edge of the reef flat the atoll slopes continuously at an approximate [illegible] slope to depths which exceed 200 fathoms.

7. The constant presence of the westerly trade winds heavily influences wind and weather conditions at Bikini Island. These winds are most uniform during the winter months of December through March when the average wind speed is about 18 knots. During the rest of the year, winds are generally reduced in speed and variable between westerly and southwesterly. The rare tropical storms passing the atoll usually come from the southeast. Rainfall is on the order of 3 in. per month in the winter, increasing during the rest of the year up to 7 or 8 in. per month. Temperatures are very uniform with daily averages of 81° to 83° F throughout the year (Emery, Tracey, and Ladd 1954). Survey information at Bikini Island indicates a mean tide range of 3.0 ft. The National Oceanic and Atmospheric Administration (NOAA 1985) reports for Bikini Atoll a mean tide range of 3.4 ft, a spring range of 4.9 ft, and a mean tide level of 3.0 ft above the mean lower low water (mllw). Measured tidal data at Kwajalein Atoll, 190 n.m. south-southwest of Bikini, are given in Table 1 (NOAA 1985).

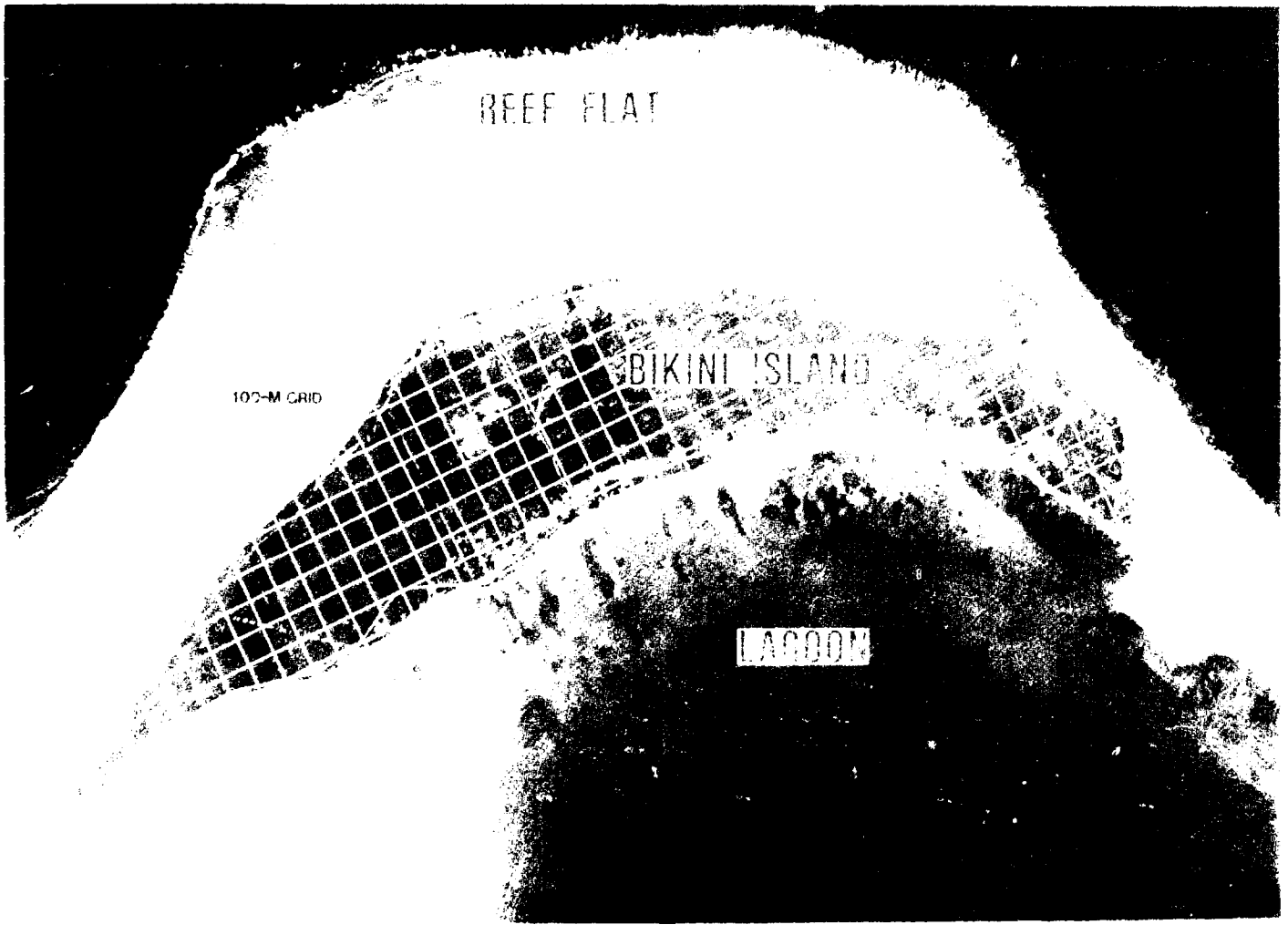

Figure 3. Bikini Island (grid lines 100 m apart, provided by BARC)

Table 1

Tidal Data from Kwajalein Atoll

Water Level	Elevation* ft
Maximum high water	6.3
Mean high water	4.7
Mean sea level	3.0
Mean low water	1.3
Mean lower low water (datum)	0.0
Maximum low water	-0.8

* Referenced to mllw.

PART II: REVIEW OF PERTINENT LITERATURE AND DATA

Sources of Information

8. Two lists of references, a bibliography of references reviewed but not cited and a reference list of works that were cited in this report, are included at the end of the main text. Reports 1 and 2 of BARC (Kohn et al. 1984, 1985) provide general historical information related to the evacuation of Bikini Atoll, the subsequent nuclear weapons tests, and the following efforts to prepare for resettlement. These two reports describe each of the alternatives proposed to date for dealing with the contaminated soil on Bikini Island. Their references include reports by the Lawrence Livermore National Laboratory and others regarding the specific effects of the nuclear weapons tests which were published independently of BARC studies.

9. The US Geological Survey (USGS) was employed during the course of the nuclear weapons tests from 1946 to 1952 to conduct intensive studies of the natural environment of Bikini Atoll and the Marshall Islands, in part to provide a baseline for assessment of the nuclear weapons effects. The work of the USGS involved extensive field measurements and analyses by many recognized experts whose individual technical reports are consolidated in USGS (1954-1969). The papers of this collection concerning the geology (Emery, Tracey, and Ladd 1954) and physical oceanography (Munk and Sargent 1954) of Bikini Atoll are of the most interest with respect to design of coastal works.

10. There is little information directly addressing extreme wind, wave, or water level conditions at Bikini Atoll; however, a number of accounts are available of storm effects at other Pacific atolls (e.g., Blumenstock 1961; Maragos, Graham, and Beveridge 1973). Extreme winds, waves, and water levels in the Marshall Islands are almost exclusively caused by tropical cyclones, known as typhoons (hurricanes) in their fully developed stage. The most extensive and useful information on typhoon characteristics and measured parameters of historical typhoons in the western north Pacific is available through various reports of the Joint Typhoon Warning Center (JTWC) on Guam. The Annual Reports of the JTWC (Buckmaster et al. 1959-1979) include detailed accounts of each tropical cyclone in the region from its earliest identification to its decay into an extratropical phenomenon. General descriptions of tropical cyclone characteristics and forecasting techniques developed for the Gulf

and Atlantic coasts of the United States are presented by the National Weather Service (NWS 1979). The Shore Protection Manual (SPM 1984) and other publications of WES also provide technical guidance for estimating wind, wave, and water level extremes, both by tropical and extratropical events.

Tropical Cyclone Data

11. Tropical cyclones comprise a unique class of atmospheric circulation phenomena which develop over tropical waters. They are warm-core, nonfrontal, low-pressure centers whose formation process is not yet fully understood. The tremendous energy required to develop and sustain the high wind velocities often associated with tropical cyclones is available only in the moisture-laden air over the tropical oceans. Tropical cyclones usually develop within 20 deg latitude of the equator and decay as they move into midlatitudes or pass over a large land mass on an average northwesterly track in the northern hemisphere. Coriolis forces cause winds to circulate counterclockwise about the center of a tropical cyclone in the northern hemisphere and clockwise in the southern hemisphere, typical of all low-pressure systems (Brand and Blelloch 1976a,b). A narrow band of maximum winds usually develops, encircling a relatively calm center 4 to 40 n.m. in diameter known as the eye. Beyond the band of maximum winds are spiraling bands of torrential rain. Wind speeds generally decline with distance from the center in these outer regions of the cyclone, but can affect sites hundreds of miles away (Weir 1983).

12. Intensities of tropical cyclones, as characterized by maximum sustained (1-min average) wind speeds at a 10-m elevation, are commonly classified as follows (Shaw 1981):

a. Tropical disturbance. A distinct system of apparently organized convection, originating in the tropics or subtropics, having a nonfrontal character, and maintaining its identity for 24 hr or more.

b. Tropical depression. A tropical cyclone in which the maximum sustained wind speed is 33 knots (38 mph) or less.

c. Tropical storm. A tropical cyclone in which the maximum sustained wind speed is between 34 and 63 knots (39 and 73 mph).

d. Typhoon (or hurricane in the Atlantic Ocean). A tropical cyclone in which the maximum sustained wind speed is between 64 and 129 knots (74 and 149 mph).

e. Super typhoon. A tropical cyclone in which the maximum sustained wind speed is greater than 130 knots (150 mph).

13. The "central pressure index" (CPI) of a tropical cyclone represents the maximum pressure gradient from the central minimum sea level pressure, usually measured in millibars (mb), to normal atmospheric pressure (typically taken as 1,013.3 mb). The "speed of movement" of a tropical cyclone is the speed at which the storm center travels along its track, usually ranging from 5 to 30 knots. Tropical cyclones passing within 180 n.m. of Guam between 1948 and 1980 had a mean speed of movement of 11.7 knots (Weir 1983). The "radius to maximum winds" is the radial distance from the center (point of minimum sea level pressure) to the location of maximum winds just beyond the perimeter of the eye. This last parameter is applied in a number of empirical techniques for forecasting wave generation and other effects, but is virtually impossible to measure. The eye diameter can occasionally be observed by aircraft or satellites when jet stream winds shear away obscuring clouds. The radius to maximum winds must often be taken by investigators as an arbitrary increase of the eye radius. This study assumes the radius to maximum winds is 20 percent greater than the eye radius (one half the observed eye diameter).

JTWC Annual Reports

14. The Annual Reports of the JTWC (Buckmaster et al. 1959-1979) present a narrative account of the event's history, a chart of the cyclone track with key observations noted (Figure 4), tabulations of the forecasts which were made by JTWC, and tabulations of observations made by radar, aircraft, and satellites for each tropical cyclone of the year. These observations include the latitude, longitude, and time of fixes of the center; the minimum sea level pressure; wind speeds and directions; and rare eye diameters. Charts of seasonal cyclone tracks are also presented with summary narrative discussions.

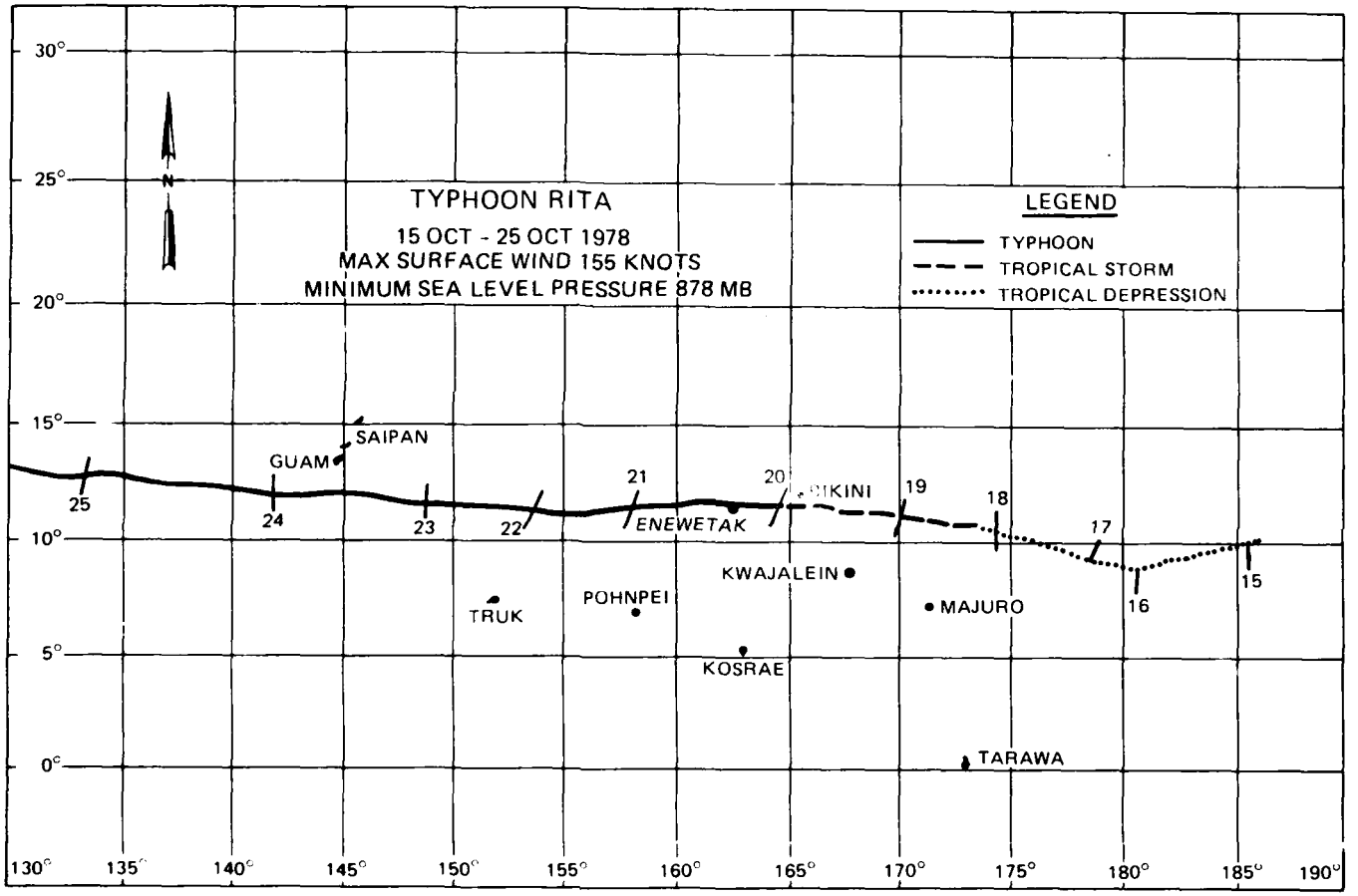

Figure 4. Track of Typhoon Rita (1978)

PART III: TYPHOON DATA ANALYSIS

Initial Sample

15. The track of each tropical cyclone documented in the JTWC Annual Reports was first inspected to see how close the storms passed to Bikini Atoll. The bulk of the storms in the 21-year record from 1959-1979 passed hundreds of miles south or west of Bikini, indicating that the northern Marshall Islands lie off the beaten path of most tropical cyclones in this region of the Pacific. Weir (1983) noted that most typhoons which passed within 180 n.m. of Guam were first identified as tropical storms (wind speeds >34 knots) well south and west of Bikini Atoll, as illustrated in Figure 5.

16. An initial data set was tabulated of tropical cyclone parameters at closest approach to Bikini Atoll for those cyclones which passed within 300 n.m. of the atoll. This initial sample includes 59 events whose key parameters are presented in Table 2. The data given in the table include the date of closest approach, followed by the location (latitude and longitude) and distance d from Bikini in nautical miles at that time.* The bearing of the storm center off Bikini Atoll ϕ_b, measured clockwise from true north, is listed next, followed by the clockwise angle from true north of the storm track ϕ_t taken as pointing toward the center of a compass rose. The arithmatic means of the 59 events for these two angular measurements were 188 deg (bearing south of the Bikini Atoll) and 130 deg (travelling northwest), respectively. The speed of movement at closest approach V_f is next noted in knots (nautical miles per hour), usually taken as a daily average. The central pressure P in millibars is followed by the central pressure index ΔP with reference to 1,013.3 mb normal atmospheric pressure. The radius to maximum winds R was estimated as 60 percent of the nearest eye diameter observation if one was observed within 2 days of closest approach. The mean radius to maximum winds (12.4 n.m.) for those events whose eye diameter was observed was assumed for events with no observation.

17. The distributions of CPI and speeds of movement were found to fit commonly applied extremal distribution functions quite well, as indicated by Figures 6 and 7. The lack of precise observations of eye diameter and the

* For convenience, symbols and abbreviations are listed in the Notation (Appendix A).

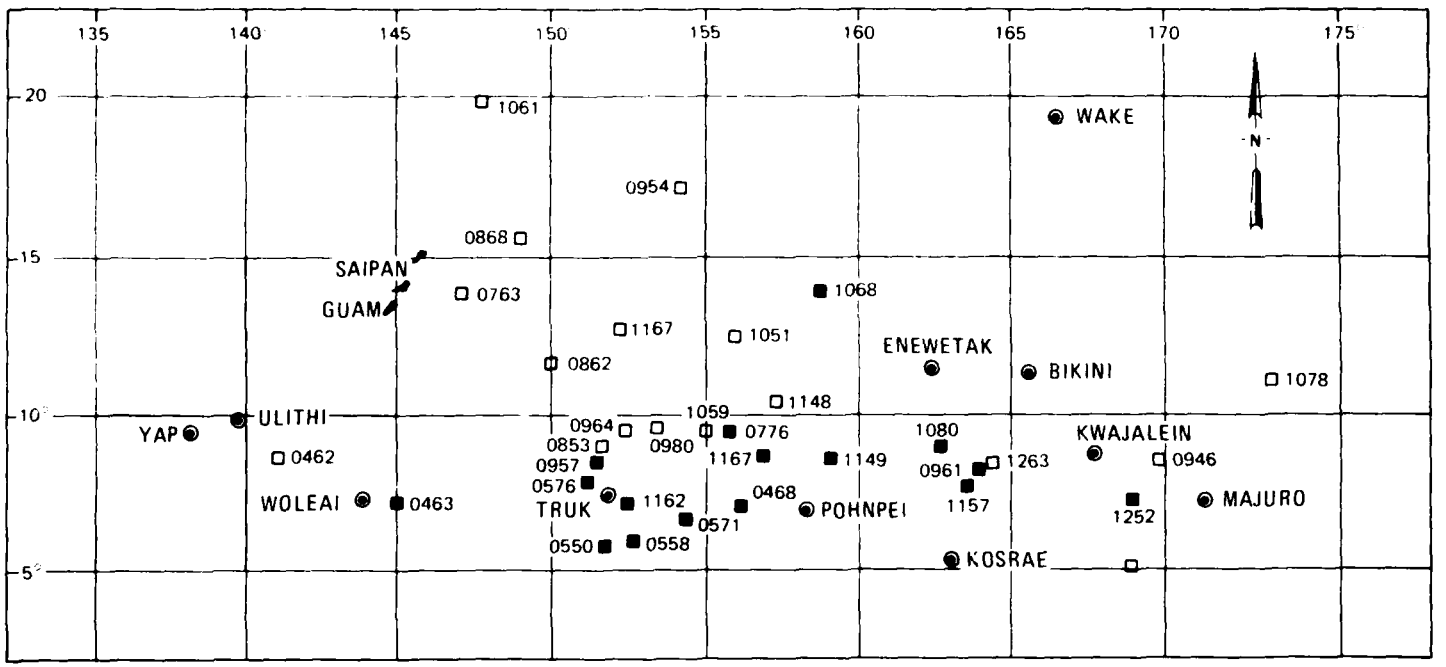

Figure 5. Points and dates at which typhoons passing within 300 n.m. of Guam were first classified as tropical storms with winds exceeding 34 knots. (Numbers indicate month and year of occurrence. Solid symbols indicate typhoons with winds exceeding 100 knots at closest approach to Guam.)

Table 2

Tropical Cyclones Within 300 n.m. of Bikini Atoll

Name	Date	Location of Center	d n.m.	ϕ_b	ϕ_t	V_f knots	P mb	ΔP mb	R n.m.	T_s sec	H_s at Bikini ft	U_{max} at Bikini knots
Abby	11-30-79	6.6 N, 166 E	295	176	86	7	990	23.3	12.4*	9.9	0	0
TD-14	8-17-79	13.0 N, 167 E	130	49	132	8	1,007	6.3	12.4*	10.1	0	0
Alice	1-4-79	9.5 N, 165.5 E	125	180	90	8	963	50.3	12.4*	10.4	0	0
Rita	10-19-78	11.5 N, 165.5 E	12.4	180	90	15	967	46.3	12.4*	11.1	26.8	71.0
Phyllis	10-14-78	11.0 N, 164 E	100	251	159	7	±992	21.3	12.0	9.9	5.4	11.6
TD-14	8-13-78	8.5 N, 163 E	220	220	119	15	1,000	13.3	12.4*	10.9	0	0
Nadine	1-8-78	9.9 N, 163 E	175	239	137	5	996	17.3	12.4*	9.6	0	0
Mary	12-26-77	9.8 N, 166.5 E	115	153	72	13	977	36.3	12.4*	10.8	5.1	12.5
Lucy	11-27-77	7.4 N, 167.3 E	225	171	80	6	987	26.3	12.4*	9.8	0	0
Jean	10-27-77	14.6 N, 162 E	285	293	293	6	989	24.3	23.4	10.2	0	0
Therese	8-7-76	9.8 N, 163.2 E	180	232	222	8	903	110.3	12.4*	11.4	0	0
Nancy	4-25-76	10.4 N, 163.7 E	155	238.5	138	21	984	29.3	12.4*	11.6	0	0
Violet	12-15-72	9.1 N, 168 E	275	127	188	2	995	18.3	12.4*	9.2	0	0
Olga	10-24-72	12.1 N, 165.5 E	35	0	90	15	939	74.3	12.4*	11.5	8.7	26.4
Nancy	10-17-72	15.9 N, 166.3 E	260	8	98	11	915	98.3	12.4*	11.5	0	0
Marie	10-6-72	13.9 N, 165.3 E	155	355	88	10	936	77.3	12.4*	11.0	0	0
Kathy	9-28-72	10.6 N, 164.5 E	95	224	125	16	976	37.3	12.4*	11.1	8.01	19.5
TD-21	9-11-72	9.9 N, 165.3 E	115	185	96	8	980*	33.3*	12.4*	10.1	4.54	11.6
Alice	8-31-72	12.9 N, 160.9 E	295	267	188	7	964	49.3	12.4*	10.2	0	0

(Continued)

* Mean value.

Table 2 (Continued)

Name	Date	Location of Center	d n.m.	ϕ_b	ϕ_t	V_f knots	P mb	ΔP mb	R n.m.	T_s sec	H_s at Bikini ft	U_{max} at Bikini knots
Viola	7-21-72	16.2 N, 166.1 E	280	5	107	18	980	33.3	12.4*	11.3	0	0
Tess	7-9-72	13.1 N, 167.2 E	150	45	149	6	940	73.3	12.4*	10.5	0	0
Phyllis	7-4-72	6.5 N, 165 E	300	185	67	10	944	69.3	12.4*	10.9	0	0
Nina	6-5-72	15.0 N, 162 E	300	316	301	13	980*	33.3*	12.4*	10.7	0	0
Lulu	5-27-72	7.7 N, 163.5 E	265	209	254	2	926	57.3	12.4*	9.8	0	0
TD-02	4-4-72	7.3 N, 163.1 E	260	207	283	10	1,001	12.3	12.4*	10.3	0	0
Faye	10-3-71	11.2 N, 165.4 E	12.4*	181	93	8	992	21.3	6.0	9.8	16.2	35.8
Patsy	11-13-70	14.3 N, 165 E	185	353	82	22	906	107.3	10.2	12.3	0	0
Marge	10-24-70	8.5 N, 165.5 E	170	180	90	3	987	26.3	12.4*	9.4	0	0
Kate	10-7-70	7.5 N, 165.3 E	245	179	89	4	986	27.3	12.4*	9.6	0	0
Hope	9-20-70	16.2 N, 165.9 E	300	4	96	14	997	16.3	7.2	10.7	0	0
Olga	6- -70	7.2 N, 165.5 E	270	180	90	28	943	70.3	6.0	11.9	0	0
Elsie	9-17-69	15.1 N, 165.2 E	230	355	139	6	999	14.3	6.0	9.3	0	0
Rita	3-8-69	7.0 N, 164 E	285	197	285	10	993	20.3	12.4*	10.3	0	0
Phyllis	1-17-69	9.0 N, 164.5 E	215	198	82	18	977	36.3	15.0	11.5	0	0
Ora	11-19-68	7.3 N, 163.7 E	300	212	111	21	995	18.3	18.0	11.8	0	0
Nina	11-16-68	9.0 N, 162.1 E	300	237	99	10	995	18.3	12.4*	10.3	0	0
Lola	11-5-68	10.0 N, 164 E	130	145	87	9	998	15.3	12.4*	10.1	0	0
Kit	10-25-68	9.0 N, 165.9 E	155	173	91	8	959	54.3	12.4*	10.4	0	0
Judy	10-21-68	11.8 N, 165.9 E	30	59	145	13	987	26.3	24.0	11.2	16.32	32.16

(Continued)

* Mean value.

Table 2 (Concluded)

Name	Date	Location of Center	d n.m.	ϕ_b	ϕ_t	V_f knots	P mb	ΔP mb	R n.m.	T_s sec	H_s at Bikini ft	U_{max} at Bikini knots
Faye	10-1-68	8.0 N, 163.8 E	235	205	119	10	996	17.3	1.8	10.0	0	0
Polly	8-3-68	11.5 N, 162.5 E	200	270	193	6	964	49.3	12.4*	10.1	0	0
Harriet	11-16-67	9.7 N, 165.1 E	120	193	94	14	992	21.3	6.0	10.6	0	0
Emma	10-27-67	7.1 N, 164.9 E	270	188	105	14	991	22.3	12.4*	10.8	0	0
Amy	9-24-67	11.0 N, 169.2 E	115	250	154	7	996	17.3	3.0	9.6	0	0
Marie	9-29-66	14.4 N, 167.8 E	230	35	120	6	998	15.3	21.0	9.9	0	0
Hester	4-4-66	7.0 N, 164.4 E	230	185	104	9	998	15.3	18.0	10.3	0	0
Faye	11-15-65	9.3 N, 164.8 E	135	191	105	7	1,001	12.3	12.4*	9.9	0	0
Della	10-11-65	11.4 N, 164.5 E	65	82	353	8	995	18.3	12.4*	10.0	9.95	19.62
TD-36	10-8-65	7.1 N, 163.5 E	290	191	111	9	996	17.3	12.4*	10.1	0	0
Carmen	9-31-65	8.5 N, 163.7 E	205	211	118	10	1,000	8.3	12.4*	10.3	0	0
Lucy	8-14-65	11.4 N, 170.2 E	275	92	94	10	993	20.3	15.0	10.4	0	0
Ellen	10-8-64	8.7 N, 166.3 E	180	165	81	6	980*	33.3*	12.4*	9.9	0	0
Susan	12-21-63	8.3 N, 164.9 E	190	100	102	10	982	31.3	15.0	10.5	0	0
Mamie	12-11-63	8.3 N, 164.2 E	215	191	111	11	999	14.3	12.4*	10.4	0	0
Lola	10-4-63	8.2 N, 164.4 E	215	194	106	12	998	15.3	12.4*	10.5	0	0
Freda	10-28-62	10.0 N, 164 E	235	245	114	10	1,003	10.3	12.4*	10.3	0	0
Nancy	9-7-61	8.6 N, 164.3 E	245	204	88	12	978	35.3	15.0	10.8	0	0
Ophelia	11-21-60	8.6 N, 165 E	185	188	94	10	1,007	6.3	12.4*	10.4	0	0
Faye	9-21-60	12.5 N, 165.4 E	65	177	89	10	994	19.3	15.0	10.4	13.2	25.5

* Mean value.

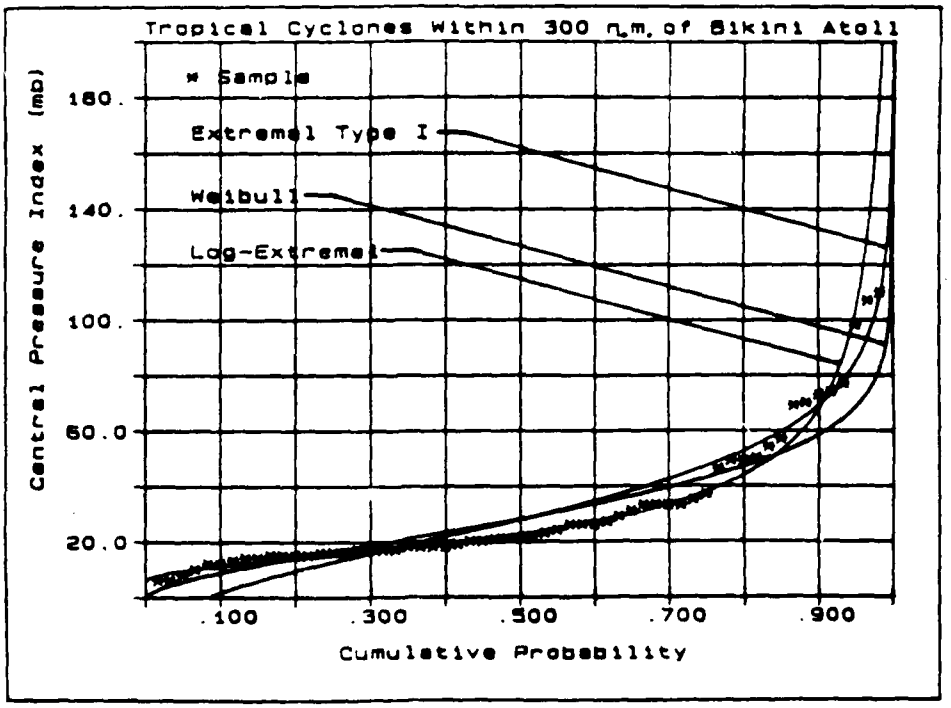

Figure 6. Cumulative probability distribution of central pressure indexes

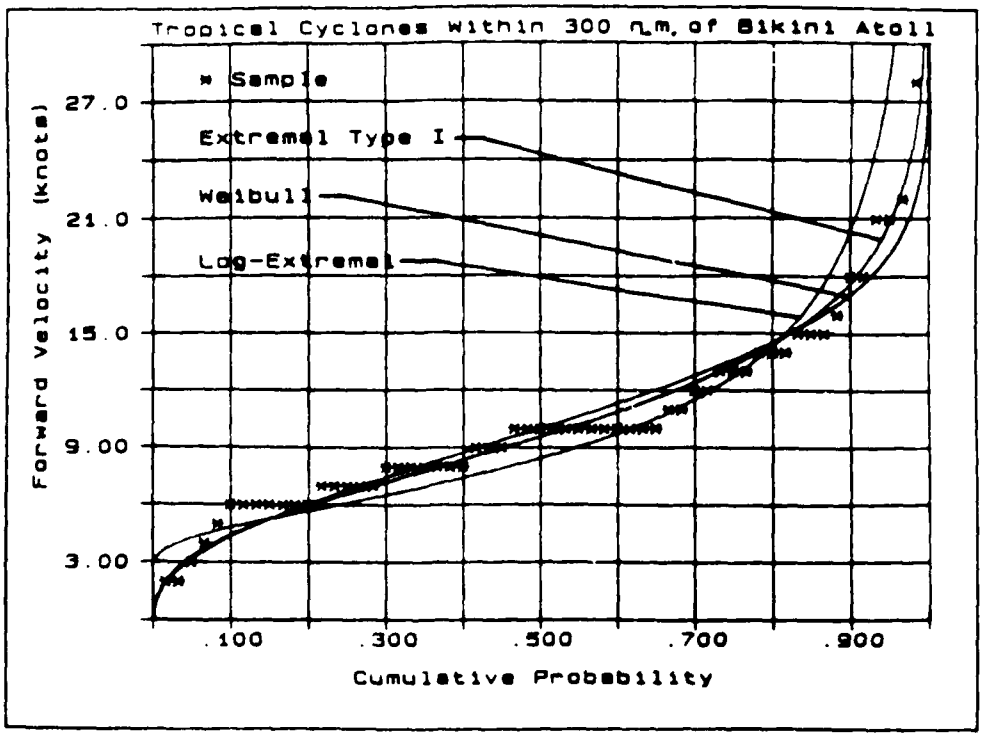

Figure 7. Cumulative probability distribution of speed of movement

general remoteness of the tracks from Bikini Atoll confounded application of these parameters as independent measures of cyclone intensity. Therefore, Figures 6 and 7 could not be used for design purposes. A number of schemes combining track and distance parameters were attempted with no success, insofar as developing a trustworthy scheme of design criteria forecasting of extreme conditions at Bikini Atoll. An alternative approach to direct application of the observed cyclone parameters, with a smaller data set, was finally adopted.

Estimation of Deepwater Wind and Wave Conditions

18. The procedures presented in the SPM (1984) were applied for estimation of deepwater significant wave height H_s, significant wave period T_s, and maximum sustained wind speed U_{max} of a hurricane with each set of parameters for the 59 events of the initial sample (Table 2). This method collectively utilizes the various parameters characterizing the tropical cyclones. It includes a graphical method for estimating the reduction of wind speeds and the corresponding reduction in wave heights with distance outward from the point of maximum winds. Figure 8 is taken from the SPM (1984) illustrating the variation of this effect with position relative to the storm track. The last three columns of Table 2 include estimates of the cyclone-induced wind and wave conditions in deep water off Bikini Atoll. The estimated effects at Bikini Atoll of most of the 59 events in the initial sample were negligible. This simplified approach does not directly address water level effects, nor does it account for swell waves which travel beyond the storm's immediate influence. However, the calculated significant wave height and wind speed account for the effect of low atmospheric pressure (CPI), forward velocity V_f, and radius to maximum wind R. It also includes the effect of distance from Bikini of most typhoons in this region, which is a more significant factor than their localized intensity. A smaller sample, including only those events with some likelihood of affecting conditions at Bikini, is therefore appropriate. A reduced sample including the 24 tropical cyclones which passed within 180 n.m. of Bikini Atoll was subsequently adopted for statistical analyses. Figures 9 and 10 illustrate the distribution of the H_s and U_{max} estimates at Bikini Atoll. The most extreme event of this sample proved to be Typhoon Rita which passed within a few miles of Bikini Atoll on 19 October 1978.

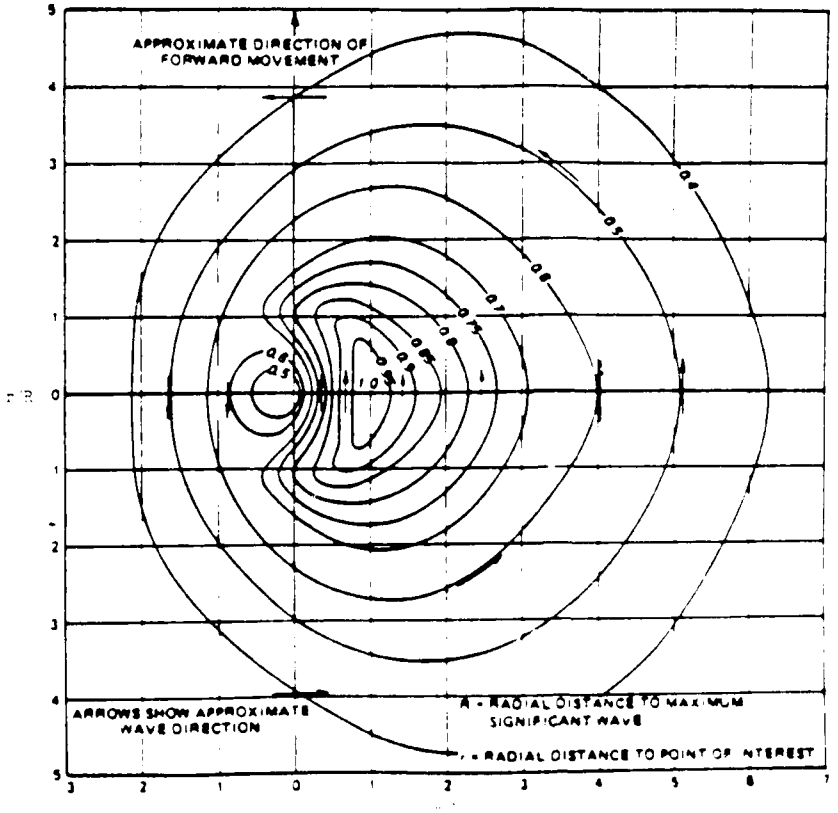

Figure 8. Variation of wave height with distance from cyclone center

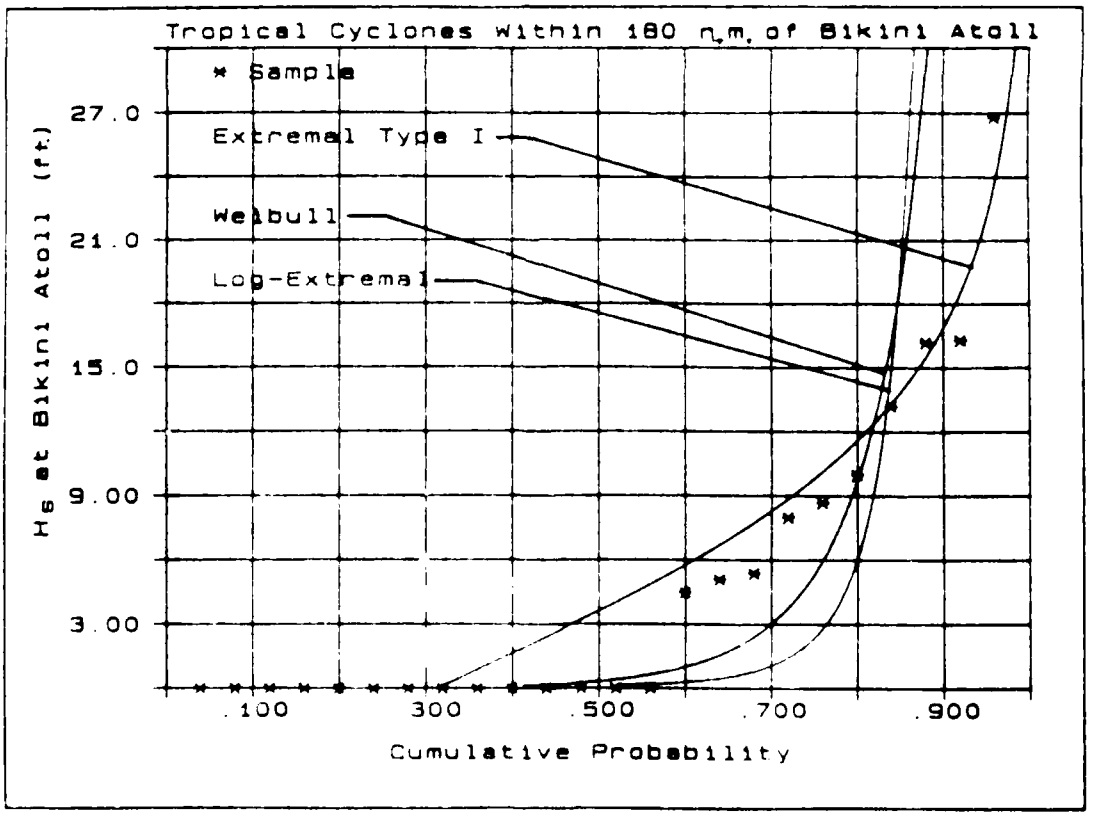

Figure 9. Cumulative probability distribution of significant wave heights

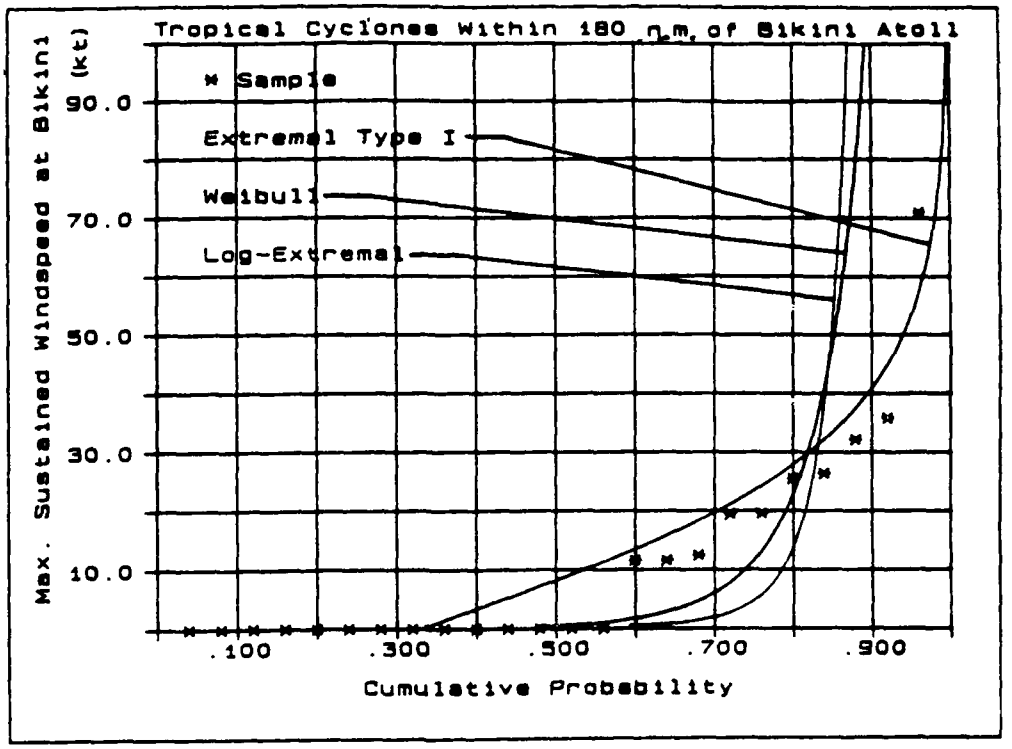

Figure 10. Cumulative probability distribution of maximum sustained wind speeds

Selection of Deepwater Design Criteria

19. It is a common practice in coastal engineering to address design criteria in two categories: functional performance and structural integrity. The special situation proposed for Bikini Island as the subject of this study causes the two criteria to be the same in a practical sense. The intended function of a revetment on the proposed landfill would be to contain the contaminated material for many years with little risk of a breach. Structural integrity criteria are varied as an economic trade-off between construction costs and future maintenance costs. Maintenance in this situation would be replacement of displaced revetment material, which would be accompanied by a failure of the structure's intended function. The two categories can thus be combined in these special circumstances.

20. The question of how much risk of failure is acceptable is always difficult to answer, but a few practical considerations help in the case of Bikini Island. First, the constructibility of shore protection for the

landfill with locally available materials limits alternatives to rubble-mound structures built of coral limestone. Rubble-mound structures are flexible and tend not to fail in a catastrophic manner when their design conditions are exceeded. Conservative design features can be built which enhance these safety margins. A detailed risk analysis, including all potential modes of damage or failure and their associated probability distributions, is beyond the scope of this study but should be considered for future efforts. A moderately rare set of tropical cyclone effects is considered appropriate at this point.

21. The "return period" of an extreme event of specified intensity is defined as the long-term average waiting time between successive events of that intensity or greater. The return period $RT(x)$ of extreme events of intensity x can be estimated by the following formula, given the cumulative distribution function $F(x)$ and the average number of extreme events per year λ :

$$RT(x) = \frac{1}{\lambda[1 - F(x)]} \tag{1}$$

Application of this formula assumes the parameter x fully represents the effective intensity of the event and that one extreme event is not affected in any way by extreme events previous or subsequent to its occurrence.

22. The design of a rubble-mound revetment, including estimation of storm surge and wave transformations in shallow water, basically requires still water level, wave height, wave period, and wind speed criteria. Storm surge, which affects the water depth, also requires a pressure gradient, but pressure gradient and maximum sustained wind speed are related, as are wind speed and wave generation. The average wave period can increase as waves propagate great distances beyond their point of generation, but wave energy also decreases with distance travelled. Wave periods, or the relative distribution of wave energy by frequency, generally remain constant over shorter distances, such as the brief stretch between deep and shallow water at Bikini Atoll. The very shallow water across the reef flat at Bikini Island, the depth of which would be heavily influenced by storm surge, will limit the height of waves through breaking processes. Wave breaking will in turn affect the additional water level rise caused by wave setup. The estimates of U_{max} can therefore represent the overall effective intensity of a tropical cyclone,

since U_{max} directly relates to both deepwater wave conditions and storm surge water levels.

23. Application of the formula above with the Extremal Type I distribution fit to the reduced data set of U_{max} estimates (Figure 10) indicates the intensity of Typhoon Rita has an estimated return period of about 50 years. From revetment design point-of-view, this is sufficiently extreme for application as a "design event." The severity of this selected design event is measured by the maximum surface wind speed, which is estimated at Bikini Atoll as 71 knots, rather than the individual parameters characterizing tropical cyclones. As discussed in the previous paragraph, the wind speed U_{max} has an overall significance in coastal engineering design practices because it directly relates to wave height and water level computations. It also should be noted that the effect on the probability of occurrence of a particular historical typhoon event due to the proximity of its track has been accounted for in the wind speed computation. Using the same probability distribution function, the Extreme Type 1, maximum sustained wind speed, for the events of 75- and 100-year return periods are estimated to be 80 and 84 knots, respectively. Naturally, the higher wind speed would result in higher wave height and storm surge at the coastline. Events severer than typhoon Rita are not recommended for the present design analysis because:

a. The relatively wide reef flat filters out most of the high energy components in the deepwater waves through breaking and friction dissipation processes. Higher waves at the site could result from larger storm surge. However, the incremental effect of wind speed is not expected to have a significant impact on wind setup computation (Equation 9).

b. Unlike rigid-type structures, the planned landfill will be protected by large-sized rubble units. Displacement of some of the armor stones rather than a total failure is expected during events severer than the design condition. Repairing a damaged rubble structure is often economically justifiable when compared with a large first investment for an overly conservative structure.

The principal parameters of Typhoon Rita estimated at closest approach to Bikini Atoll are summarized in Table 3.

Table 3

Physical Parameters of Typhoon Rita at Closest Approach to Bikini Atoll

Parameter	Value
Date	19 October 1978
Location of center	11.5 N, 165.5 E
Distance from Bikini Island	12.4 n.m.*
Bearing off Bikini Island	180 deg
Track	90 deg
Speed of movement	15 knots
Central pressure	967 mb
Central pressure index	46.3 mb
Radius to maximum winds	12.4 n.m.**
Estimated H_s at Bikini Island	26.8 ft†
Estimated T_s at Bikini Island	11.1 sec†
Estimated U_{max} at Bikini Island	71 knots

* Assumed as worst case. The track appears to have passed directly over Bikini Atoll, which actually would be less severe than the track assumed here.

** Assumed as 60 percent of mean of observed eye diameters for other cyclones in the initial data set.

† Deepwater conditions.

PART IV: PREDICTION OF NEARSHORE EFFECTS

Storm Surge

24. During a storm the reef flat along the seaward shore of Bikini Island affects both water levels and wave heights at the location of the proposed landfill. Evaluation of these nearshore effects is important to the design of a protective revetment. The combined storm effects on nearshore water level are collectively referred to as "storm surge," a rise above normal water level. Storm surge includes the components of initial setup, pressure setup, and wind setup. Discussions of each of these surge components are provided in the following paragraphs. Wave setup is another water level effect caused by storm-induced waves in the nearshore environment, but it is not usually treated as a storm surge component. Wave setup can be significant, however, and should be included in the nearshore effects analysis. The shallowness of water depth strongly influences both the wind and wave setups. Simultaneous solutions for these two setups are therefore desirable. The following paragraphs describe the analytical methods applied for Bikini Island to estimate nearshore effects under the design storm condition.

Initial setup

25. The initial setup is a rise in water level in advance of a particular storm, the exact cause of which is, at present, poorly understood. Harris (1963) reports observations of this rise in water level along the US gulf coast. Since the causes of this water level rise are still uncertain, it is usually estimated subjectively. A conservative estimate of initial setup of 0.5 ft above mhw is included in the storm surge computation for the landfill design at Bikini Island. The nearness of very deep water and open ocean conditions to the Bikini Island shore should preclude any initial setup higher than this. The SPM (1984) presents further discussions on the estimation of initial setup.

Pressure setup

26. As implied by its name, pressure setup is a large-scale bulge in the sea surface caused by the low-pressure center of the storm and the associated pressure gradient between the center and regions beyond. A maximum pressure setup is, as expected, at the storm center, gradually decreasing with distance away from the center. Using the hydrostatic principle, the maximum

pressure setup S_p can be estimated by:

$$S_p = \frac{\Delta P}{\rho g} \tag{2}$$

where

ΔP = total pressure difference from normal atmospheric pressure (or CPI)

ρ = specific density of seawater

g = gravitational acceleration

Given a CPI of 46.3 mb for Typhoon Rita at closest approach to Bikini Atoll, the corresponding maximum pressure setup can be estimated as 1.5 ft. This worst case value is applied in subsequent estimates of storm effects since Typhoon Rita passed directly over Bikini Island.

Wind and wave setup

27. Both wind and wave setups are strongly dependent upon the water depth h and can be computed together. The governing equation for the combined wind and wave setup η is:

$$\frac{dS}{dx} + \rho g(h + \eta) \frac{d\eta}{dx} - \tau = 0 \tag{3}$$

where

S = radiation stress due to wave motion

x = longitudinal coordinate in the direction of the waves

τ = combined stress due to surface wind and bottom friction

According to the results of Saville's (1952) field study at Lake Okeechobee, Fla., this combined boundary stress can be estimated by:

$$\tau = 3.3 \times 10^{-6} \rho U^2 \tag{4}$$

where U = surface wind velocity. Gerritsen (1981) uses a wave energy dissipation model to estimate radiation stress and his result can be stated as:

$$\frac{dS}{dx} = \frac{3}{4} \frac{E}{h} \frac{dh}{dx} - \frac{3}{2} \frac{\epsilon_t}{F_r \sqrt{gh}} \tag{5}$$

where

E = wave energy density

ϵ_t = rate of wave energy dissipation

F_r = Froude number, assumed to be 1.5

This equation can be simplified by dropping the dh/dx term of the right side since the reef flat is essentially horizontal, after a steep rise from deep water. The governing equation for the wind and wave setups then becomes:

$$\rho g(h + \eta) \frac{d\eta}{dx} = \frac{\epsilon_t}{\sqrt{gh}} + 3.3 \times 10^{-6} \rho U^2 \tag{6}$$

Using Gerritsen's (1981) wave energy dissipation model and assuming that bottom friction is the dominant dissipation mechanism, the rate of dissipation can be approximated by:

$$\epsilon_t = \frac{2}{3} f_w \frac{\rho}{\pi} \left[\frac{\omega H}{2 \sinh k(h + \eta)} \right]^3 \tag{7}$$

where

f_w = bottom friction coefficient = 0.1

ω = radial wave frequency = $2\pi/T$

T = wave period

H = wave height

k = wave number = $2\pi/L$

L = wave length

The wave length L is approximated by using linear wave theory, or:

$$L = \frac{gT^2}{2\pi} \sqrt{\tanh \left(\frac{4\pi^2}{T^2} \frac{h + \eta}{g} \right)} \tag{8}$$

A finite difference form equation for estimation of the wind and wave setup can now be written as:

$$\eta_{i+1} = \eta_i + \frac{\Delta x \left(\epsilon_t\right)_i}{\rho g \sqrt{gh} \ (h + \eta_i)} + \frac{3.3 \times 10^{-6} U^2 \Delta x}{g(h + \eta_i)} \tag{9}$$

Boundary Values at Reef Edge

28. The estimation of combined wind and wave setup starts at the

offshore edge of the reef flat and proceeds in the shoreward direction at an increment Δx . Wave and surge conditions at the offshore edge of the coral reef are the basic input data to Equation 9. Figure 11 illustrates the still water level (swl) and mean water level (mwl) variation in the nearshore environment at Bikini Island. The mwl may be interpreted as the average position between the wave crest and wave trough at a given location while swl is the water level when the wave action is removed. The depth h shown in Figure 11 is the mhw depth plus the initial and pressure setups. A depth of 5 ft was assumed for nearshore analysis.

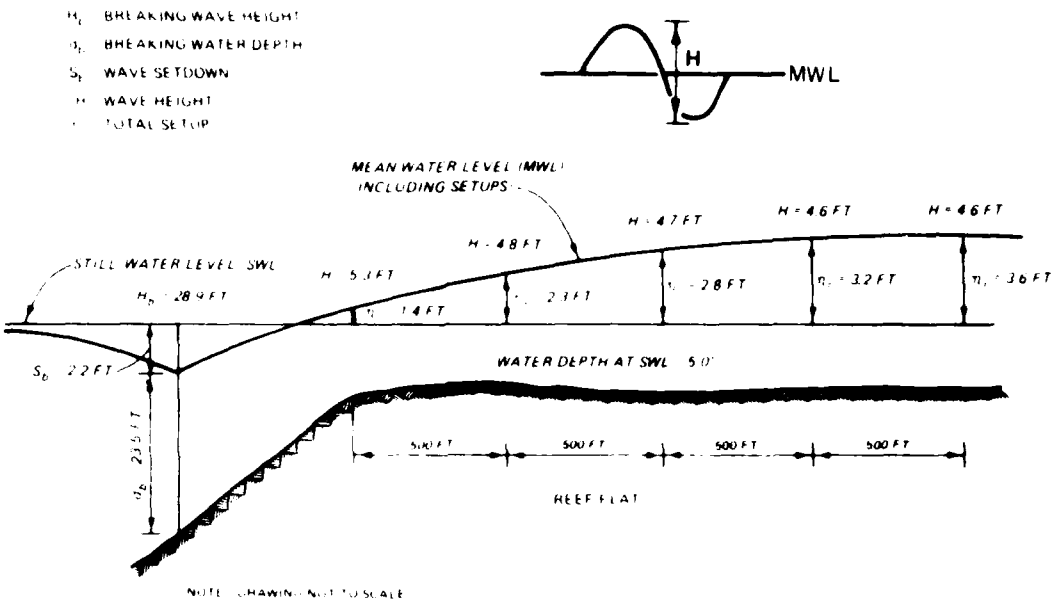

Figure 11. Schematic diagrams of water level and wave height variations

29. As waves approach the shore from the open ocean, the mwl is first depressed, as illustrated in Figure 11. This depression, referred to as wave setdown, is the result of excess momentum from the radiation stresses. The maximum wave setdown S_b is at the point of wave breaking. According to Longuet-Higgins and Stewart (1964), this maximum wave setdown may be estimated using linear wave theory as:

$$S_b = \frac{ka^2}{2 \sinh 2kd_b} \tag{10}$$

where

a = linear wave amplitude

d_b = breaking wave depth

The breaking wave depth d_b can be estimated by the following equation (SPM 1984):

$$d_b = \frac{H_b}{\frac{1.56}{1 + e^{-19.5m}} - \frac{43.75\left[1 - \exp\left(-19m\right)\right] H_b}{gT^2}} \tag{11}$$

where

H_b = breaking wave height

m = offshore bottom slope

The breaking wave height H_b can also be estimated with the method given in the SPM (1984). Under the selected design event, Typhoon Rita, the wave setdown S_b and breaking depth d_b for the significant deepwater wave are -2.2 ft and 23.5 ft, respectively (Figure 11).

30. Once the maximum wave setdown is computed, the wave setup η_r at the edge of reef flat can be estimated by integrating Equation 3 from the breaking point to the reef edge. Because of the relatively large depth, the boundary stress term in the governing equation is neglected. Here, S is calculated by using the linear wave theory, or

$$S = \frac{3}{16} \rho g H^2 \tag{12}$$

Using the same assumption as Bowen, Inman, and Simmons (1968):

$$H = \gamma(h + \eta) \tag{13}$$

which is assumed to be valid between the breaking point to the edge of the reef, the integration of Equation 3 yields:

$$\int_{\eta=S_b}^{\eta=S_r} \frac{d\eta}{dx}\, dx = - \int_{h=h_b}^{h=h_r} \frac{3/8\gamma^2}{1 + 3/8\gamma^2}\, dh \tag{14}$$

or

$$S_r = S_b - \left(1 + \frac{8}{3\gamma^2}\right)^{-1} (h_r - h_b) \qquad (15)$$

where

S_r = wind and wave setups at offshore edge of reef

h_r = water depth on top of the reef

γ = proportional constant

h_b = water depth where wave breaks

It is noted that S_b is a negative value here. Using $\gamma = 0.8$, the calculated S_r is the boundary value for Equation 9 in the computation of wind and wave setups on the reef flat. In the present analysis, $h_b = d_b = 23.5$ ft and $h_r = h = 5$ ft. Thus, $S_r = \eta_r = 1.4$ ft (Figure 11).

Wave Attenuation Along the Reef Flat

31. As the wave breaks offshore and loses a significant portion of its energy, new waves are regenerated and continue the shoreward movement. At the reef edge the maximum wave height can be estimated by H_b, such as given by Goda (1984):

$$\frac{H_b}{L_o} = 0.18 \left\{1 - \exp\left[\frac{-1.5\pi h}{L_o}\left(1 + 15 \tan^{4/3}\theta\right)\right]\right\} \qquad (16)$$

where

L_o = deepwater wave length (L_o = 631 ft for a wave period of 11.1 sec from Table 2)

θ = beach slope

The water depth in Equation 16 should include the wave setup component η_r. At the edge of the reef, a depth-limited wave height of 5.3 ft was calculated as indicated in Figure 11.

32. When waves travel across the shallow water of the reef flat, the initial heights (H = 5.3 ft) determined by Equation 16 may increase if the wind stress exceeds the frictional bottom stress of the coral reef. The initial heights at the reef edge may also decay at other times when frictional stress exceeds wind stress. An approximate method developed by Camfield (1977) is used to estimate the attenuated waves in the nearshore

environment. This method is also presented in SPM (1984) for predicting waves over flooded and vegetated land.

33. Equations 6 and 7 show the coupling processes between wave height and setup. A procedure of successive approximations on water depths ($h + \eta$) and wave heights for computing alternately wave heights and setups is devised for present nearshore analysis. This is accomplished by assuming the water depth and wave height of the entire nearshore area to be the same values at the reef edge and then computing the wind and wave setups η_r as for the first approximation. With the computed setups, water depths above the reef flat can then be computed by $h + \eta_r$. The Camfield method is used for computing the second approximation of the attenuated wave field. Refined setups distribution is obtained by inputting the new wave data into Equation 6. This alternating procedure continues until the refinements on either wave height or setup become insignificant. Two to three loops of approximation may be sufficient for desirable accuracy. The results of this procedure (given the previous estimates of initial and pressure setups, a design deepwater wave height of 26.8 ft, and a period of 11.1 sec), yield a water depth of 8.6 ft (5 ft + 3.6 ft) at 2,000 ft inshore from the edge of the reef flat and an associated depth-limited and bottom-friction-reduced wave height of 4.6 ft. The variation of mwl in these conditions is illustrated in Figure 11. This estimate is probably quite conservative given the many simplifying assumptions involved. Because of the reef effect, the design wave condition reduces from 26.8 ft offshore to 4.6 ft at the shoreline. Even with higher deepwater wave conditions (due to events severer than the design condition), the nearshore wave height will not increase appreciably enough to cause safety concerns about the landfill. A maximum increase of 5 percent in wave height and storm surge at the structure site was estimated for a 100-year event. This incremental increase would reduce to less than 3 percent for the 75-year event.

PART V: PRELIMINARY DESIGN OF REVETMENT, LANDFILL, AND BEACH FILL

Revetment Armor

34. The protection of the proposed landfill from the erosive effects of wave exposure and associated currents could be accomplished by a number of structural types. The economic advantages of simple construction with local building materials suggest a rubble-mound revetment as the ideal choice, provided suitable materials are available in sufficient quantity. A revetment of this type would consist of an outer slope of primary armor units, placed at random orientations, and underlayers between the armor and landfill sized to provide a filtering effect in the presence of hydraulic gradients. The material available locally for revetment construction at Bikini Atoll is coral limestone which could be quarried from the reef flat at Bikini Island or elsewhere around the atoll. Geotechnical fabric or "filter cloth" would probably be superior to a carefully sorted filter layer of gravel and sand and would expedite placement of primary armor. Thus, the proposed landfill could be placed at the desired geometry and covered with filter cloth, a layer of coarse gravel and cobbles (to ballast the filter cloth and cushion it from placement of primary armor), and finally the primary armor layer. The need for an additional intermediate underlayer depends on the size difference between the primary armor and the landfill material.

35. The size of rubble-mound armor unit which would be stable, i.e., resist displacement, in a given wave climate is traditionally estimated by the Hudson formula (SPM 1984):

$$W = \frac{w_r H^3}{k_d \Delta^3 \cot \theta} \tag{17}$$

where

W = stable weight of an individual armor unit

w_r = unit weight of the armor material

H = incident wave height

k_d = an empirical coefficient associated with an armor unit's relative resistance to displacement

Δ = relative specific gravity of the armor material with respect to the surrounding water

$= (w_r/w_w) - 1$

w_w = unit weight of seawater

θ = slope angle from the horizontal

The thickness B of the armor layer, placed in n courses, is estimated by:

$$B = nk_\Delta \left(\frac{W}{w_r}\right)^{1/3} \quad (18)$$

where k_Δ = layer coefficient, an empirical value equivalent to the number of cubes of the same weight which would have the thickness of the randomly placed natural material.

36. The density of the locally available coral limestone is assumed to be 140 pcf according to the BARC reports (Kohn et al. 1984, 1985), though this could vary in the course of actual quarry development. Table 4 indicates armor weights at the point of incipient damage according to the Hudson formula during the design conditions previously specified at the toe of the proposed revetment. This case indicates median weights W_{50} of a moderately graded (variable size) armor material, where the maximum weights are approximately 4 W_{50} and the minimum weights are approximately $W_{50}/8$. The gradation, in terms of diameters, is approximately $D_{85}/D_{15} = 2.29$.

Table 4

Hudson Formula Armor Weight Computations*

Structure Slope cot	Armor Weight, tons, W_{50}	Armor Thickness, ft	Number per Unit Area, sq yd
1.50	1.23	5.2	1.68
1.75	1.06	4.9	1.86
2.00	0.92	4.7	2.03
2.25	0.82	4.5	2.20
2.50	0.74	4.4	2.35
2.75	0.67	4.3	2.5
3.00	0.62	4.1	2.66
3.25	0.57	4.0	2.80
3.50	0.53	3.9	2.95
3.75	0.49	3.8	3.09
4.00	0.46	3.8	3.22

* Armor unit weight = 140 pcf; wave height = 4.6 ft; stability coefficient = 2.2 (for graded rough stone, i.e. riprap, randomly placed in two layers); armor porosity = 37 percent; layer coefficient = 1.00.

37. These alternate weight and slope combinations would be equally stable in the specified wave conditions according to the Hudson formula. This formula does not account explicitly for any effects of wave period or duration of exposure. Furthermore, the formula was developed for using monochromatic waves instead of more natural irregular waves. Van der Meer and Pilarczyk (1984) have developed a procedure from using irregular waves which measures both the effect of wave periods and duration of exposure. Their tests related primarily to quarrystone revetments on an impermeable base, which is the case at Bikini Island. The two empirical relations which apply in this case are:

$$\frac{H_s}{\Delta D_{n50}} = 1.25 \sqrt{\cot \theta} \left(\frac{S_2}{\sqrt{N}}\right)^{1/6} \xi^{0.1} \quad \text{for} \quad \xi > 3.5 \quad \text{and} \quad \cot \theta < 3 \qquad (19)$$

$$\frac{H_s}{\Delta D_{n50}} = 4.4 \left(\frac{S_2}{\sqrt{N}}\right)^{0.22} \xi^{-0.54} \quad \text{for} \quad \xi < 3.5 \qquad (20)$$

where

H_s = significant wave height of an irregular sea state, approximately equal to the average wave height of the highest one-third waves

D_{n50} = equivalent cubic dimension of the median armor size

$= (W/w_r)^{1/3}$

S_2 = dimensionless damage value, equivalent to the number of individual armor units displaced per unit armor width on the face of revetment

N = number of individual waves which strike the revetment, taken as the duration of the event of interest divided by the average wave period

ξ = surf similarity parameter

$= \tan \theta / \sqrt{H_s/L_o}$

L_o = deepwater wave length corresponding to the average period T_z

$= gT_z^2/2\pi$

38. Application of this procedure to the Bikini Island revetment design requires a number of approximations. First, the Hudson formula results are assumed as the appropriate armor weights, following Corps of Engineers standard practice. Second, the design wave height of 4.6 ft is assumed to be the significant wave height for application of Equations 19 and 20. It should be noted that the latter assumption implies a much more severe wave climate at

the project site than the design storm condition described earlier. The Van der Meer and Pilarczyk (1984) procedure is applied to indicate the optimum slope at which S_2 is a minimum. The number of waves is estimated as 2,200, assuming the design event is a typhoon moving at 15 knots which has its most significant influence while within 50 n.m. of the site, which would be a time span of 6.7 hr. The 11.1-sec significant period estimated for Typhoon Rita is applied in this approximation, as well as for computation of ξ . Table 5 indicates the results of this procedure corresponding to various slopes, given H_s = 4.6 ft, T_z = 11.1 sec, N = 2,200 , and median armor sizes computed by the Hudson formula. Since the significant wave height represents an average of the highest one third of waves, the sea state represented by H_s of 4.6 ft is severer than the sea state whose maximum wave height is 4.6 ft. The results shown in Table 5 are used for the selection of revetment slope.

Table 5

Results of Van der Meer and Pilarczyk (1984) Procedure

Slope	ξ	W , lb	D_{n50} , ft	S_2
1:1.5	7.8	2,460	2.6	15.1
1:2.0	5.8	1,840	2.4	10.7
1:2.5	4.7	1,480	2.2	7.5
1:3.0	3.9	1,240	2.1	12.4
1:3.5	3.3	1,060	2.0	23.1
1:4.0	2.9	920	1.9	20.8

39. A slope of 1:2.5 appears optimum with minimum displacement during the design event. The predicted S_2 value of 7.5 units displaced per armor unit width is a rather high value, given that the slope may extend about 40 ft from toe to crest and, thus, include an average 23 armor units in a 2.2-ft width. The procedure of Van der Meer and Pilarczyk (1984), therefore, indicates that about one third of the armor layer would be displaced when it is under the attack by waves of H_s = 4.6 ft. By considering the uncertainties of assumptions in the wave and surge analysis, a 50-percent increase in armor unit weight is incorporated to improve the safety margin of the designed revetment. It is interesting to note that this increase in unit weight

reduces S_2 from 7.8 to 3.3, which is considered to be acceptable for the design of rubble structures. Thus, 2,200-lb armor weight at a 1:2.5 slope is chosen as the median size armor material in this preliminary design analysis. This 50-percent increase in armor unit weight provides a significant safety margin in the event of a 75- or 100-year storm. An armor layer of two randomly placed courses of material this size would be approximately 5 ft thick.

Runup and Overtopping

40. The waves striking the armor slope of the revetment would swash up the slope and perhaps spill over the crest. The vertical distance up which waves swash on a slope is the "runup height," or simply "runup." Spilling over the crest is "overtopping," clearly a function of wave runup. A relation which predicts the runup on a rough slope of a wave of specified height and period (Ahrens and McCartney 1975) is:

$$\frac{R}{H} = \frac{a\xi}{(1 + b\xi)} \tag{21}$$

where

R = runup

H = incident wave height

The empirical coefficients for graded rough armor stone on an impermeable base are $a = 0.956$ and $b = 0.398$. Table 6 gives runup values predicted by this procedure, given a slope of 1:2.5, a significant wave height of 4.6 ft, and a period (assumed constant) of 11.1 sec. A Rayleigh distribution of incident wave heights is assumed to estimate the probability distribution of runup in

Table 6

Runup Estimates, 1:2.5 Slope

Probability of Exceedance, %	Runup ft
1.0	10.1
10.0	7.6
13.5	7.2
50.0	4.6

these conditions. The significant wave height has a 13.5-percent probability of exceedance according to this distribution.

41. The mean overtopping rate during this design condition would be about 0.5 ft^3/min/ft, including the added influence of a 71-knot onshore wind, if the slope extends 16 measured feet vertically above the bottom (reef flat) in 8.6 ft of water. This overtopping rate was estimated by the method described below:

$$Q = k' \left(g Q_o^* H_o^3 \right)^{1/2} \exp \left[\frac{-0.217}{\alpha} \tanh^{-1} \left(\frac{h - d}{R} \right) \right] \qquad (22)$$

where

Q = overtopping rate per unit length of structure

k' = adjustment factor for onshore wind effects

$= 1.0 + W_f \sin \theta \left[(h - d)/R + 0.1 \right]$

W_f = wind speed coefficient ($0 \leq W_f \leq 2.0$)

$\cong U^2/1800$

h = height of structure above the bottom

= 16 ft

d = water depth = 8.6 ft

R = potential runup, assuming an infinitely high slope, as computed above

Q_o^* = empirical coefficient related to specific site conditions

= 0.1 (Figure 7-28, SPM 1984)

H_o = equivalent deepwater wave height, in this case based on simple shoaling by linear wave theory

= 3.4 ft

α = empirical coefficient complementing Q^*

= 0.05 (Figure 7-28, SPM 1984)

This is an acceptably low volume of water which would not contribute to any erosion, particularly if the armor layer is extended horizontally 50 ft behind the revetment crest as a "splash apron." This configuration would provide a significant margin of safety for protection of the landfill material behind the revetment.

Cross-Section Design

42. The landfill material would consist of the sandy topsoil typical of small islands in the vicinity of Bikini Atoll, plus palm trees and other vegetation. Separate disposal of the vegetation cover would prevent minor settlement problems, which might occur in 5 to 10 years, caused by the decay of the trunks and larger branches. The sandy topsoil would be reliably contained by a filter cloth cover with a nominal ballast layer above 2 ft of gravel and cobbles, typical of quarry run material. This ballast layer, if composed of coarse gravel and cobbles, would adequately protect the filter cloth during placement of the 1- to 4-ft armor stones and would serve as a good foundation for the armor during wave attack. The surface of the reef flat is assumed to be hard and relatively impermeable, requiring no treatment as a foundation for the landfill.

43. The BARC reports (Kohn et al. 1984, 1985) estimated the volume of topsoil to be contained in the landfill as 981,000 cu yd. That estimate is assumed to be adequate for this preliminary design. The length and width of the landfill are chosen by two primary criteria. The first is to make the landfill as narrow as possible to maximize its distance from the edge of the reef and thus minimize wave energy. The second criterion involves avoidance of the most ecologically productive areas of the inshore reef flat, which are concentrated along the northern windward shore of Bikini Island.*

44. It is also desirable to minimize the destruction of the sandy beach which surrounds the island at the inside of the reef. The Bikini Islanders place a high value on this beach, according to their communications with the BARC (Kohn et al. 1984, 1985). The prospect of replacing the beach that would be lost beneath the landfill is therefore worth consideration.

45. Figure 12 illustrates a cross section of all the above considerations. The corresponding plan view is illustrated by Figure 13, which outlines the toe of the revetment. Table 7 presents the material quantity estimates which correspond to this cross section and alignment.

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* Personal Communication, March 1986, Katherine Agegian, Department of Oceanography, University of Hawaii, and James E. Maragos, US Army Engineer Division, Pacific Ocean.

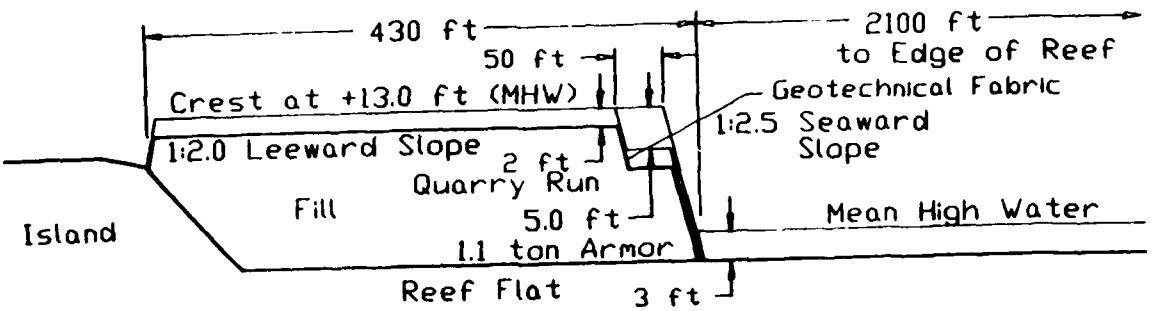

Figure 12. Landfill and revetment cross section

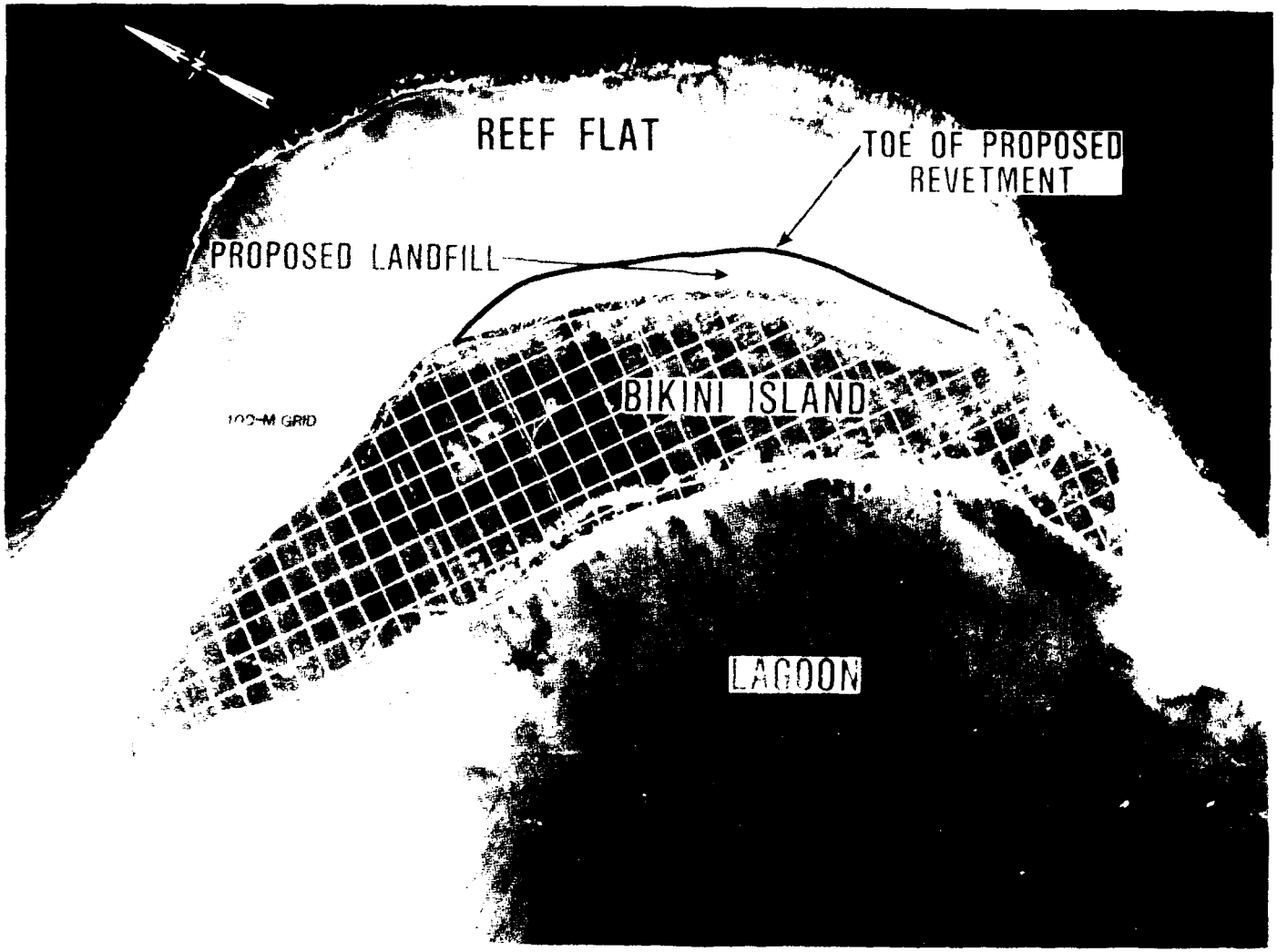

Figure 13. Landfill and revetment plan (grid lines are 100 m apart)

Table 7

Estimated Landfill and Revetment Material Quantities

Component	Material	Estimated Quantity
Landfill	Fine sand with organics	981,000 cu yd
Filter	Polypropylene geotextile	295,000 sq yd
Cover	Coarse gravel and cobbles	210,000 cu yd
Armor	Coral limestone, 2,200-lb median size	93,000 cu yd

Potential Uses of the Landfill Area

46. The landfill area, as shown in Figures 12 and 13, would be a broad expanse of level gravel without any vegetation. This would lend itself to development of light industry, where graded staging areas or storage space is desirable. Prefabricated buildings could be founded safely on such a base, though the potential settlement problems related to buried tree trunks would be of greater concern beneath any such structures. Heavier structures might also be built on the proposed landfill with correspondingly more attention paid to foundation conditions. The area could not be allowed to grow any vegetation, particularly coconut palms, however, without additional efforts to contain the contaminated topsoil within the landfill. Plant growth across the landfill area would appear more natural and be more desirable for residential or resort development. The design of more complex containment features to accomodate a vegetative cover would require investigations beyond the scope of this preliminary study. Any such features would almost certainly have a significant effect on the overall cost of the landfill project. The structural geometry of the revetment slope, the armored splash apron, and an additional margin of at least 50 ft further inshore should not be modified to this end.

Beach-Fill Design

47. A beach fill would have to be placed on the seaward side of the revetment and would be subject to intermittent losses in the event of severe storms. Much of the original beach sand could be stockpiled as beach-fill material, with additional material coming from the lagoon. Palm trees and

other vegetation, which help to stabilize natural beaches in this region, would not be possible on the rocks of the revetment. A beach fill would, therefore, not be as picturesque nor as stable as the original beach but would be more suitable for recreation or other human uses than the bare armor of the revetment. A storm of the intensity for which the revetment has been designed would almost certainly result in complete loss of the beach fill. The loss of permeability within the armor layer would temporarily reduce its stability, though the beach sand between armor units would be lost quite rapidly upon exposure to wave action. The added expense of a beach fill, which would be lost in the event of a severe storm, should be weighed against the benefits it would accrue.

48. A beach fill roughly equivalent to the natural beach in profile would extend approximately 84 ft beyond the toe of the revetment out onto the reef flat. A typical cross section of the revetment with a beach fill on its face is illustrated in Figure 14. The placement volume of this material,

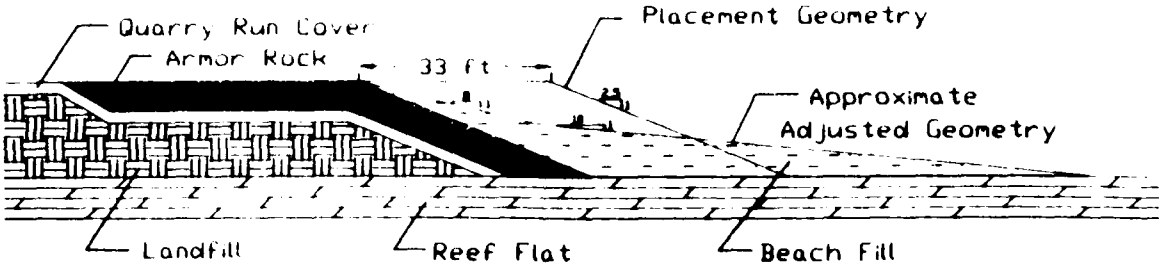

Figure 14. Revetment and beach-fill cross section

including an overfill adjustment for initial loss of fines, is estimated as 113,000 cu yd. During normal mild conditions this beach fill would rapidly adjust to ambient conditions and subsequently behave much like the original beach. Additional information on material characteristics, wave climate, and tidal currents on the reef flat is needed to refine this prediction.

Construction Methods

49. A stripping operation to first remove trees and larger vegetation and separate disposal of this material, perhaps at sea, would be desirable for use of the landfill as a foundation for buildings or other structures. Since these plants are unsafe for consumption, the disposal method should be chosen

with care. Handling of the material, i.e., transfer from one mode of transport to another, should be minimized for the sake of cost. If disposal elsewhere is not practical, trees and heavy vegetation should be placed at the bottom of the landfill and spread as thinly as possible.

50. Removal of the existing topsoil from Bikini Island would presumably involve conventional equipment and procedures. The existing structures may also be demolished, if necessary, by conventional means. Concrete buildings should be reduced to rubble and placed at the bottom of the landfill on the reef flat where their weight and any exposed reinforcement will not cause problems. Wooden structures should be broken up and disposed with the trees and large vegetation.

51. The normally mild environment at Bikini Island should allow construction of the landfill, filter, cover, and revetment without any special protective measures. Nevertheless, the construction should be timed to avoid, as much as possible, the chance of a storm during construction. Early construction of the revetment before the landfill behind is complete would alleviate much of this risk. The primary environmental concern directly related to the construction process is apparently the potentially harmful effects on the reef ecology of excess suspended sediments in the water. Temporarily high siltation in the immediate vicinity of the landfill construction will be difficult to avoid. Initial construction of an outer dike of moderately coarse material, lined with fine material or even filter cloth, would be one way to minimize an influx of suspended sediments throughout the course of the remaining work. This technique would also be useful in the proposed replacement of island topsoil with dredged sediments from the lagoon. Floating silt curtains are another alternative for reducing siltation on the reef, though these have a poor success record due to the practical problems of keeping them in place.

52. The placement of a beach fill of lagoon sediments by hydraulic pipeline would be efficient and economical, but would cause a tremendous increase in suspended sediments in the vicinity of the discharge. Placement by end dumping from trucks and grading with dozers would reduce these problems somewhat. Fine material from the beach fill would continue to be lost as the fill material responds to the ambient waves and currents. A beach-fill material as uniform and similar as possible to the native beach material would be ideal in terms of minimizing siltation problems on the reef flat.

PART VI: RECOMMENDED REFINEMENTS FOR FINAL DESIGN

Design Criteria Development

Climatology

53. The tropical cyclone climatology near Bikini Atoll should be defined with greater precision prior to formulation of final design criteria for a protective revetment. An additional data search should be undertaken, followed by simulation of a set of extremes of storm-induced wave growth and propagation in deep water. A revised deepwater extremal probability distribution of key physical parameters should be developed from these simulations.

Nearshore effects

54. The simplifiying assumptions made in this preliminary analysis regarding wave transformation to the edge of the reef, storm surge, wave breaking, wave setup, and frictional losses across the reef flat should be tested and refined by both numerical and physical modeling prior to final design. A nearshore finite-difference numerical model of wave refraction, diffraction, and shoaling from deep water to the point of breaking could better define breaker heights and depth of breaking. Such a model would account for the effects of the unique bathymetry surrounding the atoll. A separate numerical model would be necessary to economically simulate concurrent storm surge effects. A two-dimensional physical model (i.e. a wave flume test) would be necessary to refine the estimates of breaker zone characteristics and frictional losses across the reef flat. Simulation of lateral relief of the storm surge and wave setup across the reef flat to either side of the island would require innovative procedures. The influence of typhoon scale onshore winds would also be difficult to assess, unless winds can be superimposed on the scale model.

Revetment Design

55. The structural stability and functional performance of the proposed revetment should be tested in the physical scale modeling arrangement recommended above. The armor size and geometry should first be reevaluated using refined estimates of incident wave conditions, based on the numerical modeling efforts also recommended above. The physical model should measure armor

displacement, runup, and overtopping, according to conventional practice. It should account for the effects of natural irregular waves, potential wave grouping, and duration of exposure. The sequence of tests should define the long-term expected damages of alternative geometries, resulting in an optimum, cost-effective choice of armor size, slope, and crest elevation. These factors cannot be reliably estimated by purely analytical means at this time.

Field Measurements

Surveys

56. Detailed topography of Bikini Island, in particular of its windward shoreline, would be necessary for a more accurate estimation of material quantities and associated construction costs. A detailed hydrographic survey of the reef flat and nearshore regions along the windward shore would also be necessary for accurate numerical and physical simulations, as well as for estimation of material quantities.

Oceanographic measurements

57. Water surface elevation and wave and current measurements along the existing shoreline would be necessary in order to predict the stability and performance of a revetment and a beach fill. Water surface elevation measurements should be made to more precisely define pertinent tidal datums (e.g., mean lower low water, mean tide level, and mean higher high water) for reference by surveys. Wave measurements should be made outside and inside the edge of the reef flat opposite the proposed site of the landfill to measure wave attenuation of the reef in as extreme a condition as possible. These measurements could also serve to differentiate the astronomical tide from wave setup associated with the trade winds. Both tidal and wave-induced currents, preferably near the bottom, should be measured on the reef flat in the vicinity of the site of the proposed landfill.

Geotechnical measurements

58. The characteristics of the landfill, cover, revetment armor, and beach-fill materials must be precisely defined prior to final design efforts. The material characteristics of the existing windward beach, including any longshore or cross-shore variations, should also be measured. These characteristics should include size gradation, specific gravity, particle shape, and, in the case of beach material, fall velocity in seawater.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

59. Construction of a landfill on the seaward reef flat at Bikini Island protected from erosion by a revetment of locally available coral limestone appears feasible. Conventional construction equipment and techniques could be applied. Control of siltation during construction to protect marine organisms on the reef flat would be the most challenging aspect of construction. The addition of a beach fill outside the landfill would increase the problems of siltation control. Additional studies by specialists would be necessary to formulate a means to accommodate plant growth above the landfill of contaminated soil. Refinement of the landfill and revetment design should involve further field measurements of topography, hydrography, water levels, waves, and currents at Bikini Island. Additional numerical simulations of deepwater wave growth and propagation during extreme events should be followed by numerical simulations of nearshore wave transformation and water level effects. Physical modeling of wave attenuation across the reef flat at Bikini Island should be applied to optimize the final landfill and revetment geometry.

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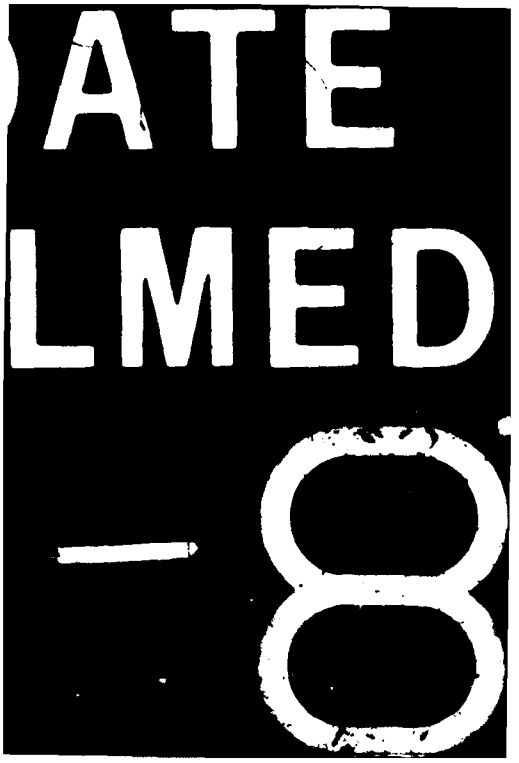
APPENDIX A: NOTATION

a	Linear wave amplitude; coefficient (0.956)
b	Empirical coefficient (0.398)
B	Thickness of the armor layer
CPI	Central pressure index
d	Distance, n. m.; water depth, ft
d_b	Breaking wave depth
D_{n50}	Equivalent cubic dimension of the median armor size
E	Wave energy density
f_w	Bottom friction coefficient
F	Cumulative distribution function
F_r	Froude number
g	Gravitational acceleration
h	Water depth; height of structure above bottom, ft
h_b	Water depth where wave breaks
h_r	Water depth on top of the reef
H	Wave height
H_b	Breaking wave height; depth-limited wave height at the reef edge
H_o	Deepwater wave height
H_s	Deepwater significant wave height, ft
k	Wave number = $2\pi/L$
k_d	Empirical coefficient associated with an armor unit's relative resistance to displacement
k'	Adjustment factor for onshore wind effects
k_Δ	Layer coefficient, for breakwater design
K	Radius to maximum wind
L	Wave length
L_o	Deepwater wave length
m	Offshore bottom slope
N	Number of individual waves which strike the revetment
P	Central pressure of a tropical storm or typhoon, mb
Q	Overtopping rate per unit length of structure
Q_o^*	Empirical coefficient related to specific site conditions
R	Radius to maximum winds of a tropical storm or typhoon; wave runup
RT	Return period of a rare event

S	Radiation stress due to wave motion
S_b	Maximum wave setdown
S_p	Maximum pressure setup
S_r	Wind and wave setups at offshore edge of reef
S_2	Dimensionless damage value, equivalent to the number of individual armor units displaced per unit armor width on the face of a revetment
T	Wave period
T_s	Significant wave period, sec
T_z	Average period
U	Surface wind velocity
U_{max}	Maximum sustained wind speed, knots
V_f	Speed of tropical storm/typhoon movement, knots
w_r	Unit weight of the armor material
w_w	Unit weight of seawater
W	Stable weight of an individual armor unit
W_f	Wind speed coefficient
x	Extreme events of intensity; longitudinal coordinate in the direction of the waves
α	Empirical coefficient
γ	Proportional constant
Δ	Relative specific gravity of the armor material with respect to the surrounding water
ΔP	Central pressure index
ϵ_t	Rate of wave energy dissipation
η	Combined wind and wave setup
η_r	Wave setup
θ	Beach slope, angle from the horizontal
ϕ_b	Bearing of storm center off Bikini Atoll measured clockwise from true north
ϕ_t	Clockwise angle from true north to the storm track, taken as pointing toward the center of a compass rose
λ	Average number of extreme events per year
ξ	Surf similarity parameter = $\tan \theta / \sqrt{H_s/L_o}$
ρ	Specific density of seawater
τ	Combined stress due to the surface wind and bottom friction
ω	Radial wave frequency = $2\pi/T$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